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PROPOSED INCORPORATION OF MISSION-ORIENTED FLYING QUALITIES INTO MIL-STD-1797A

DAVID G. MITCHELL & ROGER H. HOH
HOH AERONAUTICS, INC.
VISTA VERDE CENTER #217
2075 PALOS VERDES DRIVE, NORTH
LOMITA CA 90717

BIMAL L. APONSO & DAVID H. KLYDE
SYSTEMS TECHNOLOGY, INC.
13766 S. HAWTHORNE BLVD
HAWTHORNE CA 90250

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WRIGHT LABORATORY
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This technical report has been reviewed and is approved for publication.

THOMAS J. CORD
Project Engineer
Control Dynamics Branch
Flight Control Division

SIVA S. BANDA, Chief
Control Dynamics Branch
Flight Control Division

DAVID P. LEMASTER
Chief, Flight Control Division
Flight Dynamics Directorate

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David G. Mitchell and Roger H. Hoh of HOH Aeronautics, Inc. and Bimal L. Aponso and David H. Klyde of Systems Technology, Inc.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Systems Technology, Inc.
13766 S. Hawthorne Blvd
Hawthorne CA 90250

HOH Aeronautics, Inc.
Vista Verde Center #217
2075 Palos Verdes Dr. N.
Lomita CA 90717

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13. ABSTRACT *(Maximum 200 words)*
The effort documented in this report was undertaken to revise the flying qualities military standard, MIL-STD-1797A, in both form and content. It was felt that mission-oriented requirements on new systems would expand the applicability of the standard to all tasks performed in an operational environment. This allows replacement of Flight Phases and reference to aircraft weight with a series of Mission-Task-Elements. Demonstration maneuvers are included to be an independent assessment of handling qualities. Additionally, much of the work done in the definition of flying quality criteria in the twelve years since the MIL-STD was originally proposed has been incorporated. These modifications deal generally with task amplitude, system response type, and control feel system characteristics. Two other important changes are the guidance provided on use of alternative requirements and the linking of flying qualities Levels and the Cooper-Harper Handling Qualities Rating Scale. The results of this effort are expected to be a cornerstone in the process to create MIL-STD-1797B and will be subject to critical review by the aerospace industry as well as a Tri-Service Review Team.

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FOREWORD

The work presented herein was performed during the period from May 1992 to October 1994 under Contract F33615-92-C-3604 from the Flight Control Division, Flight Dynamics Directorate, Wright Laboratory, Air Force Materiel Command. The Air Force Project Engineer was Mr. Thomas J. Cord of WL/FIGC-2, Mr. Duane T. McRuer was the STI Technical Director. The initial STI Project Engineer was Mr. David G. Mitchell. This duty was later transferred to Mr. Bimal L. Aponso.

The authors wish to acknowledge the contributions of individuals at both STI and Wright Laboratory. The enthusiasm and dedication of all the evaluation pilots were key to the success of the piloted simulation conducted as part of this effort. The evaluation pilots were Lt Col. Michael J. Costigan, Maj. Paul Weaver, Maj. Greg Jaspers, Maj. Doug Benjamin, Captain Bruce DeWitt, and Captain Gregory L. Miller of the USAF; and Mr. Roger H. Hoh of Hoh Aeronautics, Inc. We gratefully acknowledge the assistance of Lt Col. Costigan in the setup of the evaluation tasks. At STI, we are grateful for the assistance of Mr. Theodore J. Rosenthal in reducing and analyzing the experimental data; and Mr. Charles W. Reaber and Ms. Donna Taylor of the publications staff, in report graphics and typing.

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SECTION I

SUMMARY OF PROPOSED CHANGES TO MIL-STD-1797A

This report documents the results of a Phase II Small Business Innovative Research (SBIR) contract to develop proposed revisions to the flying qualities military standard, MIL-STD-1797A (Ref. 1). The intent of these revisions has been to create a structure for making MIL-STD-1797A a mission-oriented specification. The following is a brief summary of the proposed changes. Included in these changes are several recommendations for enhancing MIL-STD-1797A in general. The latter are not specifically related to mission-oriented flying qualities and hence are discussed only in the following.

A. MISSION-ORIENTED REQUIREMENTS

Define requirements based on realistic mission elements, not Flight Phases. These Mission Task Elements are defined in terms of a real maneuver, and ultimately every Mission Task Element will have a corresponding flight test demonstration maneuver (discussed below) defined for it. This is perhaps the most significant "mission-oriented" step proposed in this report. It is thus the subject for considerable discussion throughout the report.

Eliminate reference to aircraft size (Class). A number of the requirements in MIL-STD-1797A have different values depending upon aircraft size, defined in terms of four Classes of aircraft. This division is actually somewhat arbitrary, and is sometimes irrelevant. For example, if a particular mission requires a high level of aggressiveness and precision, it should not matter if the airplane proposed for that mission is small or large. Only the mission requirements should set flying qualities. It is recognized that, in some cases, this may lead to unreasonable demands on very large airplanes. As an example, if a large transport is required to perform ground attack, the Level 1 roll performance limits stated for fighters may be unachievable without the use of extremely fast actuators and the possible introduction of very high lateral accelerations at the pilot's station. In this case, it should be obvious that either 1) a new Mission Task Element, *transport ground attack*, with relaxed mission demands, needs to be defined, or 2) it is simply not possible to build a Level 1 transport for the ground attack task.

Add demonstration maneuvers as an integral part of the standard. It is recognized that the quantitative requirements of MIL-STD-1797A are not now, and can never hope to be, completely comprehensive. Meeting these requirements does not guarantee desirable handling qualities. Conversely, failing one or more of the requirements is not necessarily a guarantee of less than desirable handling qualities (although it is highly probable). Qualitative flight test evaluations should be made an integral

part of the specification to provide an independent assessment of handling qualities. Currently the standard is a flying qualities document only: it tests the dynamics of the aircraft alone, without regard for the possible influences of task details, or the pilot's operating environment (other than turbulence). Addition of demonstration maneuvers allows for two separate methods for assessing the Levels of handling (as opposed to flying) qualities:

1. **Predicted Levels based on flying qualities parameters.** This is the current method, consisting of comparisons with quantitative boundaries of flying qualities parameters. When establishing compliance, the aircraft's flying qualities parameters are determined and compared with the boundaries appropriate to its operational requirements. A Level 1 aircraft must meet the Level 1 standards for all of the criteria. The quantitative criteria are based on previous experiments and analyses, and hence result in predicted Levels of handling qualities.

2. **Assigned Levels based on flight test maneuvers.** The second method of establishing Levels is to perform a set of well-defined flight test maneuvers using a team of at least three pilots. These pilots assign HQRs to the aircraft for each maneuver. The average HQR determines the Level for each maneuver and a Level 1 aircraft must be rated Level 1 for all of the maneuvers designated as appropriate to its operational requirements. Compliance with the flight test maneuvers is based on piloted evaluations, and therefore results in assigned Levels of handling qualities.

Acknowledge the possibility of different dynamic response characteristics (response type). One shortcoming of several of the requirements of MIL-STD-1797A is that they are not applicable to all response types. For example, aircraft with pitch attitude command/attitude hold dynamics should not be evaluated using the CAP criteria for short-term response. The number of different response types possible for fixed-wing airplanes is not extensive, so this amounts, in essence, to simply amplifying the guidance to the user. No real restructuring of the standard is required. See Appendix B.

Allow for the degrading effects of loss of visual cuing. This is a major step in producing a *handling* qualities, as opposed to flying qualities, specification. The importance of visual cuing was investigated briefly for this study, as documented in Appendix B.

Introduce more comprehensive requirements. As a part of the study reported here, a piloted simulation was conducted to develop new requirements for moderate-amplitude maneuvering — an area not adequately covered by MIL-STD-1797A. Appendix A documents the simulation, and the new requirements are included in Section V. Also as a part of this study, and under sponsorship from other sources, several new and revised existing requirements were developed and are presented in Section V of this report. These requirements, including limits on flight path Bandwidth and roll Bandwidth, help make the standard more complete as well as more mission-oriented.

B. GENERAL CHANGES

Develop a consistent procedure for dealing with the effects of the cockpit control feel system. There is some disagreement over the importance of the dynamics of the feel system on pilot opinion. Currently MIL-STD-1797A is inconsistent in addressing the feel system. Most requirements explicitly exclude it, some explicitly include it, some require both ways, and still others do not say. There are data to support all of these approaches, but a specification should never be ambiguous. Section IV of this report shows support for including the feel system at all times, at least until a comprehensive set of requirements can be developed that deal exclusively with the flying qualities effects of the feel system.

Get rid of the "fill-in-the-blanks" format. Despite reasoned arguments to the contrary (Ref. 2), MIL-STD-1797A is a "cookbook" document, as is required of the MIL Prime Standard format. All of the "recipes" for the standard are given in the Handbook, attached to the standard as Appendix A. This theoretically provides a structure for tailoring of the requirements to a particular procurement. Unfortunately, it seems to lead only to confusion. In most cases the only recommended requirement given is straight out of the predecessor, MIL-F-8785C, so no "tailoring" is likely in this case. In other instances, such as for the short-term pitch requirements, the choices are presented with no real guidance to the user as to the best for a particular application, so it is likely again that the selected requirement will be that taken directly from MIL-F-8785C.

Where alternative requirements exist, provide guidance to the user. This is especially important for the pitch response requirements mentioned above, where several of the alternatives are not applicable to all aircraft. It should be assumed that future users will not always be highly experienced experts in handling qualities, so such guidance will be critical. Proposed guidance for the pitch requirements is presented in this report.

Tie the definitions of flying qualities Levels directly to the Cooper-Harper Handling Qualities Rating (HQR) scale (Ref. 3). This recommendation has been made before (Ref. 4). It is based on the acknowledged relationship between the HQR scale and all of the requirements in MIL-STD-1797A. There is some association with the current Level definitions, but a more complete relationship should be made. There are justifiable concerns about how to interpret the requirements in conditions of degraded operating conditions, but these concerns exist now as well. The Army's helicopter specification (Ref. 5) and currently proposed tri-service MIL Standard (Ref. 6) both state Level explicitly in terms of the HQR scale. This subject is discussed more in Section V.

Make the Handbook easier to read and follow. Appendix A of MIL-STD-1797A needs a table of contents. In addition, because some of the discussions in the Appendix are quite long, it is easy to get lost when paging through the document. Footers identifying the paragraph number should be added to each page. This was done for the user's guide for the Army's helicopter flying qualities specification, ADS-33C (Ref. 7), and is extremely useful.

SECTION II

BACKGROUND

A. THE NEED FOR UPDATING MIL-STD-1797A

The military standard MIL-STD-1797A (Ref. 1) represents the currently best available resource for flying qualities guidance and criteria. Most of the specific requirements contained in Appendix A of the standard have not been extensively revised since the release of MIL-F-8785B (Ref. 8) in 1969; slight revisions were made for the last specification, MIL-F-8785C (Ref. 9), in 1980, and in the proposed standard that was developed in 1982 (Ref. 10). MIL-STD-1797A does represent a significant upgrade from MIL-F-8785C in terms of criteria that can be applied to the flying qualities of highly-augmented aircraft, but the need for a mission-oriented document was identified even before the draft version of MIL-STD-1797A was written. Recently, several efforts have been initiated to produce mission-oriented flying qualities specifications for both V/STOLs (Ref. 11) and rotorcraft (Refs. 5, 6, and 7).

Some of the more significant deficiencies of the current MIL-STD-1797A are as follows:

- The Flight Phases are not fully representative of modern aircraft missions. For example, none of the maneuvers associated with agility (e.g., Herbst turn) are included. In addition, many advanced aircraft are flown in partially automatic modes (e.g., Integrated Fire/Flight Control, IFFC) for portions of their missions, yet such "automatic flight" elements are either absent from the Flight Phase list, or are only hinted at. In either case, there is no guidance as to the proper application of the existing Flight Phases for such operations.

- The grouping of the Flight Phases into three Categories has resulted, in some instances, in inappropriate application of criteria. For example, Landing (L) is a terminal Flight Phase, in Category C; for some aircraft, however, the stringent requirements for precision landing make this task more like a tracking task, which is Category A. This deficiency was exposed for the USAF's STOL and Maneuver Technology Demonstrator (S/MTD), where the landing was redefined to be a Category A task for the control law design process (Ref. 12). A mission-oriented document would differentiate between wholly non-precision landings (e.g., transports on 10,000 ft runways under benign conditions) and precision landings (e.g., the S/MTD on a battle-damaged 1500-ft runway).

- There is little or no information on requirements for advanced digital fly-by-wire, multi-mode aircraft. Such aircraft have a wide range of possible control laws, allowing task-tailoring and definition of novel response schemes (response types). Much of this technology was known in 1982, but it has matured significantly in the last decade to the point that the mission-oriented standard must reflect the different possible response types available.

- There is no guidance for the user when competing criteria are presented, such as for short-term pitch requirements, where several of the alternatives are simply not applicable to all

response types. For example, the "preferred" short-term pitch criteria are based on Control Anticipation Parameter (CAP), which has stood largely unchanged from MIL-F-8785B. While such requirements may be appropriate for conventional airplanes whose response characteristics are "classical" (e.g., Refs. 13 and 14), they are entirely incorrect for attitude systems and can be misleading for rate systems (e.g., Ref. 15).

- As the standard has become a specialized document for flying qualities, it has lost one of the attractive features of the older specifications: its use by flight control systems engineers as a design tool. While this is not the *purpose* of the MIL Standard, it is a justifiable objective. The future mission-oriented standard must provide a method for communications between the designers and flying qualities specialists early in the design process. It should, as a result, help assure aircraft that will meet the flying qualities requirements without any major "surprises" during developmental testing.

- The well-known interaction between the pilot's visual environment (displays and vision aids) and handling qualities is not reflected at all in MIL-STD-1797A. A metric for relating handling qualities and the pilots' visual environment, the Usable Cue Environment metric, was developed for Ref. 5 and is sorely needed in a mission-oriented standard. This will provide a medium for communications between the display specialists and handling qualities engineers as well.

- The standard contains requirements for small-amplitude maneuvering and for control power, but there are no criteria for the moderate-amplitude region in between. Such maneuver amplitudes relate to aircraft agility and criteria should be developed and incorporated.

- A very serious shortcoming of MIL-STD-1797A is the lack of any formal, final "proof-of-concept" measure: Appendix A of the standard discusses rationale, guidance, and lessons learned for verification of each requirement, but there is no way to assure that compliance with all of the individual requirements will produce an acceptable article. A limited set of demonstration maneuvers, representative of the most important mission elements, is needed as a final verification. Such maneuvers have been included in the Ref. 5 rotorcraft specification.

- There are many criteria and design guidelines that have been developed or revised in the last decade that are not included in the MIL Standard.

B. OBJECTIVES OF THIS STUDY

The primary objective of this study has been to create the structure for a mission-oriented flying qualities military standard. As a part of this objective, several of the flying qualities criteria themselves were evaluated and recommended revisions have been assembled.

Included in the objectives were assessments of the impact of visual cuing and aircraft response type on the standard, and the need for flight test demonstration maneuvers. Not all of these objectives could be completely achieved. For example, while there is an obvious requirement for demonstration

maneuvers, the justification for incorporating the concept of visual cue environment was not found to be as strong.

C. ORGANIZATION OF THIS REPORT

Each of the major objectives of this study is discussed in the main text of this report, and in some cases in more detail in the appendices. Section III outlines the concepts for a mission-oriented military standard, including new proposed Flight Phase Categories, based on the introduction of Mission Task Elements (MTEs). Section IV reviews recent research data concerning the effects of the airplane's feel system dynamics on flying qualities to propose that the feel system be included in all flying qualities assessments. Section V provides a detailed analysis of the current version of MIL-STD-1797A (Ref. 1) with recommended modifications to existing criteria, as well as new criteria based on the results of a piloted simulation.

In Appendix A the piloted simulation conducted for this study is documented, with some analysis of the results. Appendix B elaborates on the investigation of the role of visual cuing, response type, and MTES on flying qualities. Appendix C outlines the concepts for demonstration maneuvers. Appendix D focuses on the issue of force and displacement requirements for sidestick controllers, including recommended requirements for the military standard. In Appendix E supporting data and discussions are provided for several of the revised and new short-term response criteria described in Section V.

SECTION III

CONCEPTS FOR A MISSION-ORIENTED FLYING QUALITIES MILITARY STANDARD

A. MISSION FLIGHT PHASES

It is desirable to categorize segments of the missions into flying qualities tasks. The ability of the aircraft to accomplish these tasks is measured according to the appropriate criteria. It is not practical, or necessary, to derive a separate set of criteria for every defined task. Instead, the tasks are grouped in terms of the criteria boundaries that apply to them. In the current MIL-STD-1797A (Ref. 1) and its predecessors MIL-F-8785B and C (Refs. 8 and 9), the mission tasks were grouped in terms of the following three "Flight Phase Categories:"

Category A:	Those nonterminal Flight Phases that require rapid maneuvering, precision tracking, or precise flight path control.
Category B:	Those nonterminal Flight Phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight path control may be required.
Category C:	Terminal Flight Phases, normally accomplished using gradual maneuvers and usually requiring accurate flight path control.

Mission tasks are listed under each of the above categories, although no definition of the tasks is contained in the specification.

The mission tasks in the mission-oriented specification will be more formally defined as "Mission Task Elements" or MTEs. It is intended that the MTEs be specified in detail, including desired and adequate performance limits. All future flying qualities experiments accomplished in support of MIL-STD-1797A should utilize the MTEs, and the Cooper-Harper Handling Qualities Ratings (HQRs) should be based on the performance included in the MTE definitions. This procedure is prescribed to overcome a primary deficiency wherein the tasks used in handling qualities experiments, which define the criterion boundaries, are only loosely related to the mission tasks.

The above Flight Phase Categories have been revised to eliminate the distinction between terminal and nonterminal tasks, which is irrelevant in terms of the appropriate criterion boundaries to apply. In addition, the MIL-STD-1797A categories have been found to have the following deficiencies:

- Category A is too broad, ranging from air-to-air combat to reconnaissance.

- Category B is too lenient and should apply only to flight in Visual Meteorological Conditions (VMC).

- Category C is not sufficiently stringent for the precision landing typically performed in flight research, and Category A is too stringent for that MTE.

For the mission-oriented specification, the Flight Phase Categories are defined in terms of the required *precision* and *aggressiveness*. Four categories are defined as follows:

- Category A: Tasks that are precise and aggressive.

- Category B: Tasks that are non-precise and non-aggressive.

- Category C: Tasks that are precise and non-aggressive.

- Category D: Tasks that are non-precise and aggressive.

To the extent possible, the categories have been defined to retain as many of the same tasks as in previous versions of the specification. The relationship between the old and new Flight Phase Categories is summarized in Figure 1. The definitions of the new Flight Phase Categories are given below.

1. CATEGORY A: Tasks that require precision and aggressiveness

This category includes precision tasks, where an extremely crisp and predictable response to control inputs is required. Ride qualities are typically not a factor. The results of not achieving the required precision are usually significant in terms of accomplishing the mission or safety of flight, e.g., terrain following.

The new Category A is similar to the old Category A, but more stringent in terms of pilot aggressiveness required to accomplish the MTEs. The less aggressive precision tasks have been placed in Category C.

2. CATEGORY B: Tasks that do not require significant precision or aggressiveness

Non-precision tasks that require only a moderate amount of closed-loop control fall in this category. The most stringent task is non-precision landing, which is intended to imply the existence of moderately long runways. This is similar to the old Category B, but is more stringent in that it includes landings, waveoffs, and takeoffs — all MTEs that used to fall in Category C. This could cause some complaints

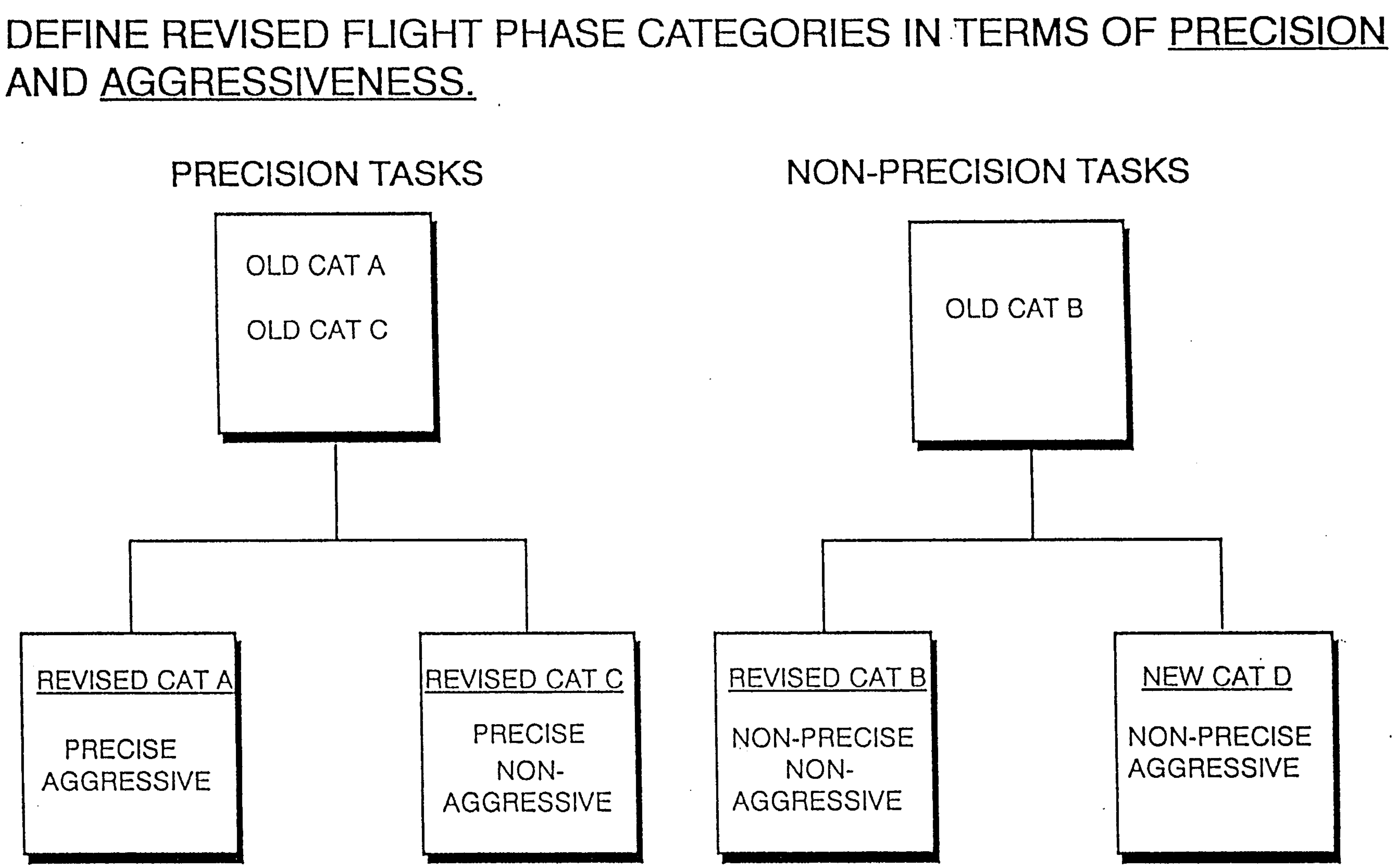


Figure 1. Proposed New Flight Phase Categories

from manufacturers since it effectively increases the requirements for Category B MTEs. The rationale is as follows:

- Most of the classic up-and-away Category B tasks are usually done on autopilot.
- The flying qualities required for Category B in MIL-STD-1797A are marginal (e.g., dutch roll damping $\zeta_d \geq 0.08$ and natural frequency $\omega_d \geq 0.40$ rad/sec) for anything but day VMC without turbulence. Since military airplanes are rarely restricted to VMC, it is felt that the handling qualities should reflect Instrument Meteorological Conditions (IMC). Qualitatively, the dynamic requirements for up and away IMC flight are similar to those for non-precision landings (and hence are in the same Category). If data shows that the landing task is more stringent, a special boundary or limit can be imposed for that MTE, similar to the dutch roll damping requirement for CO and GA in the present specification.

3. CATEGORY C: Precision tasks that do not require aggressive control activity

This category includes tasks where considerable precision is required, but without the aggressive control activity associated with the Category A MTEs. The dynamic response requirements for Category C are expected to be less than for A, but significantly greater than for B. This category includes many of the old Category A MTEs.

4. CATEGORY D: Non-precision tasks that require aggressive maneuvering

This category is intended to include the large amplitude maneuvering MTEs that emphasize control power over crisp dynamics. It is true, however, that a reasonably good dynamic response is inherently necessary to effectively utilize a large amount of control authority, i.e., to stop and start the large amplitude maneuvers with some precision (recall the old control power vs. damping plots). The moderate- and large-amplitude maneuvering requirements will be of primary interest for Category D MTEs. This is a new category, and it will invoke some of the existing control power criteria, as well as the new attitude quickness or other agility criteria.

A tentative categorization of MTEs into each of the four Flight Phase Categories is given in Table 1. All of the mission tasks from MIL-STD-1797A are included as MTEs as well as some new tasks that have evolved in recent years. Some mission tasks in MIL-STD-1797A were too broad, such as Air Combat. These have been broken down into definable flying qualities tasks in Table 1. The intent of the groupings in Table 1 is that the requirements in a given category are sufficiently similar so that a single criterion boundary will apply. For example, the Bandwidth criterion should have the form shown in Figure 2.

TABLE 1. CATEGORIZATION OF MISSION-TASK-ELEMENTS

CATEGORIZATION OF MISSION-TASK-ELEMENTS			
Non-Precision Tasks		Precision Tasks	
Non-Aggressive (Category B)	Aggressive (Category D)	Non-Aggressive (Category C)	Aggressive (Category A)
Reconnaissance (RC)	Gross acquisition using loaded roll	Aerial recovery (AR)	Tracking maneuvering target (CO)
In-flight refueling - tanker (RT)	Missile defense with loaded roll	In-flight refueling as receiver (RR)	Ground attack (GA)
VMC and IMC loiter/cruise/ climb/descent (including emergency descent) (LO, CR, CL, D, ED, DE)	Anti-submarine search and maneuvering (AS)	Low altitude parachute extraction (LAPES)	Weapon delivery and launch (WD)
Normal takeoff (TO)	High speed max g turn	Catapult takeoff (CT)	Terrain following
Waveoff/go-around (WO)	"Herbst" turn	Approach (PA)	"Herbst" turn
Non-precision landing (L)	Split S, chandelle, hammerhead turn, loop, barrel roll, snap roll, etc.	Precision landing	Precision aerobatics, e.g., 8 point roll, etc.
	Scissors, high and low speed "yo-yo"	Close formation (FF)	
		Tactical final approach	

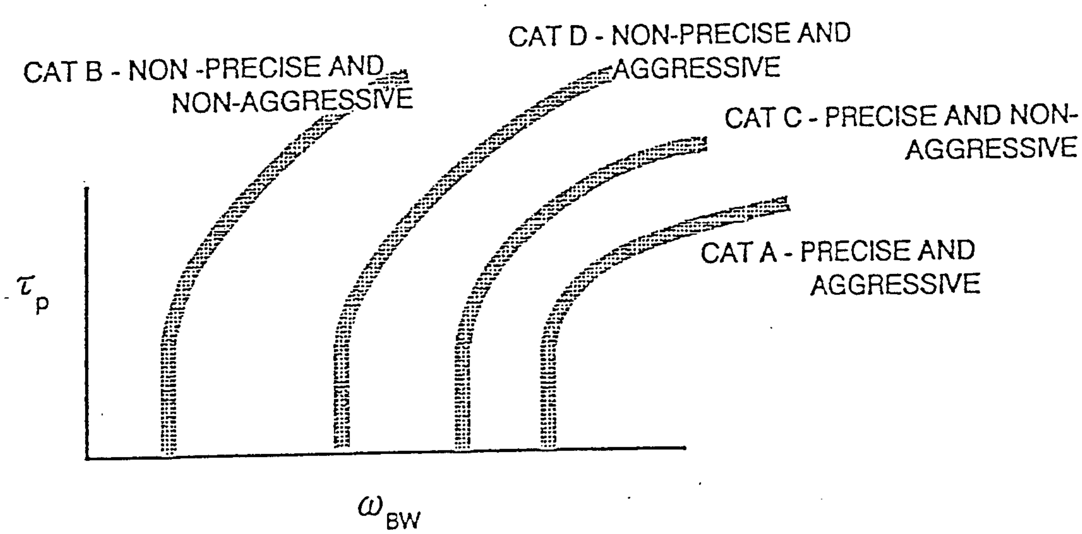


Figure 2. Illustration of Relationship Between Categories and Specification Boundaries

B. INTRODUCTION OF CONCEPT OF RESPONSE TYPE

The term response type refers to the shape of the response, characterized in either the time domain (response to a step controller input) or frequency domain (Bode plot). It is included to allow a distinction to be made between the response shape and the dynamics as defined by CAP, Bandwidth, etc. Some common response types are attitude command/attitude hold (ACAH), rate command/attitude hold (RCAH), or basic unaugmented dynamics (or combinations of feedbacks) that make an airplane look "conventional" (e.g., Ref. 13). Generic characteristics of these common response types are shown in Figure 3. Experience has shown that the "best" response type can depend on the task, or Mission Task Element in the proposed new jargon. For example, Table 2 presents the advantages and disadvantages of several response types for the Precision Landing MTE.

Ideally MIL-STD-1797A would contain such a table for all of the MTEs, thereby providing guidance for the flight control designer as to the preferred control system architecture. Modern digital fly-by-wire aircraft are capable of mode switching so that the pilot may have the best flight characteristics for each mission task. The concept of response types as illustrated in Figure 3 and Table 2 provides the necessary guidance to successfully accomplish such "task tailoring."

C. THE USABLE CUE ENVIRONMENT

The importance of the pilot's visual environment on the ability to perform required tasks is well established. What is not as obvious, however, is the significant impact the visual environment can have on the required handling qualities of the vehicle. In this context we are referring to the *total visual environment available to the pilot* — including not only out-the-window views (if applicable), but all cockpit head-up and head-down displays and gauges. In the past, the visual display has been considered to be a critical element for task *operation* — i.e., either the pilot has enough information to perform the task or he doesn't. More recent studies (e.g., Refs. 16 and 17) have clearly demonstrated a direct relationship between the visual environment and handling qualities as well — i.e., the visual field may be *sufficient* for the required operation, but not *satisfactory* without increased workload. A simple example of this is the use of a digital airspeed readout on a HUD: it provides airspeed information, but it may be difficult for the pilot to read and interpret compared to a moving-tape display.

Figure 4 illustrates the relationship between field of view, microtexture, and Cooper-Harper Handling Qualities Rating for a precision low-speed task with a helicopter (Ref. 16). The research of Ref. 16, and others that followed, resulted in definition of a Usable Cue Environment (UCE) scale for the rotorcraft

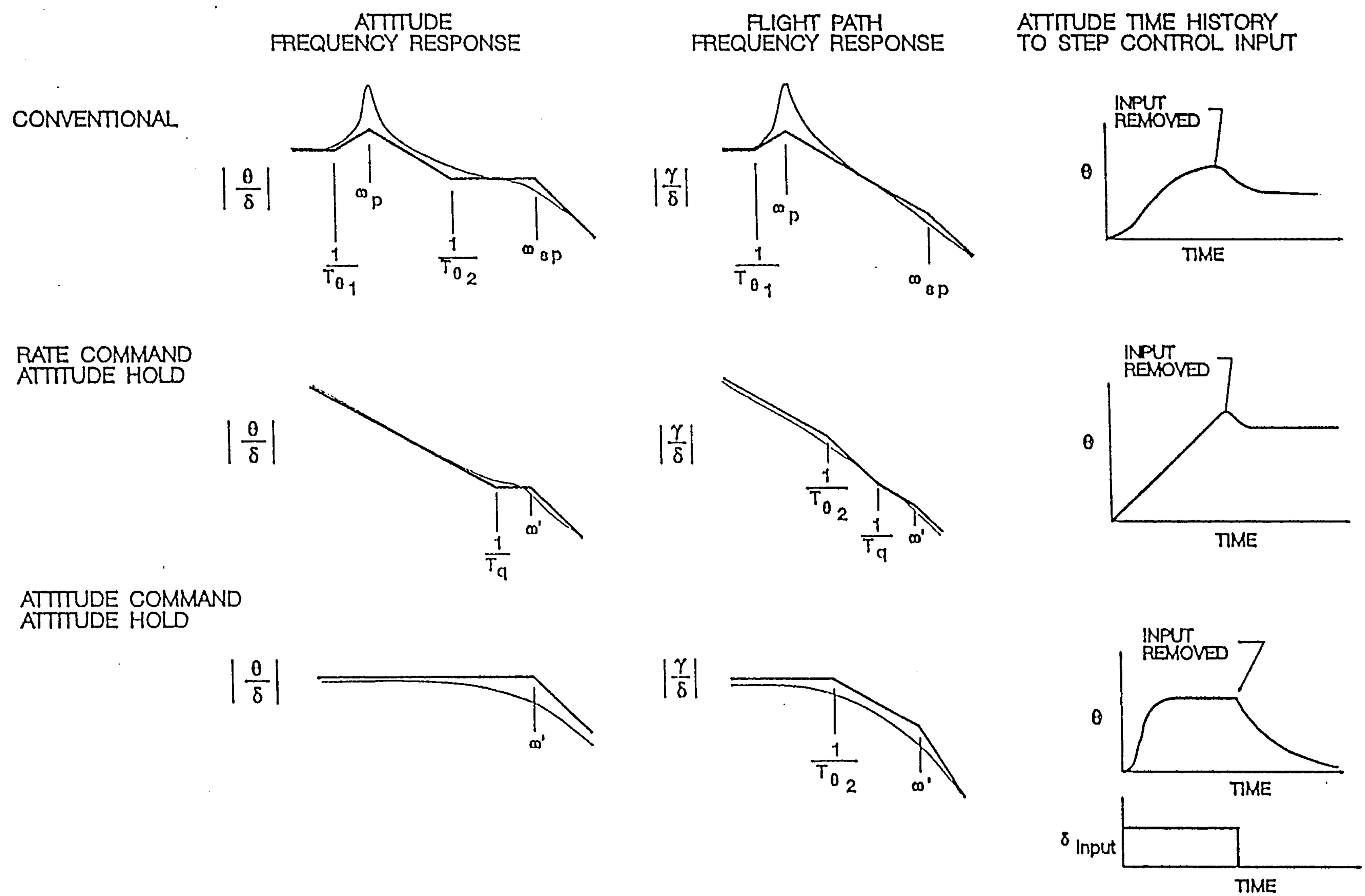


Figure 3. Generic Characteristics of Three Response-Types

TABLE 2. QUALITIES OF SEVERAL RESPONSE-TYPES FOR THE PRECISION LANDING MTE

Response-Type	Advantages	Disadvantages
Conventional Airplane	Well accepted flare characteristics	Lightly damped phugoid mode. Requires trimming to change airspeed during the approach. Angle-of-attack sensing required—gust sensitivity problems.
Rate Command/Attitude Hold (RCAH)	No trimming required to accomplish airspeed changes during the approach.	Not as desirable for flare. Not Level 1 if $1/T_q > 1/T_{\theta_2}$. (see Figure 2) Tendency to float in flare. Tendency for airspeed control problems during the approach (associated with division of attention).
Attitude Command/Attitude Hold (ACAH)	Highly desirable flare characteristics.	Requires trimming during approach.
Flight Path Command/Flight Path Hold	Highly desirable flare characteristics	Requires trimming during approach. May result in excessive speed bleedoff for unpowered approach in windshear. Sensing requirements more complex than for ACAH.

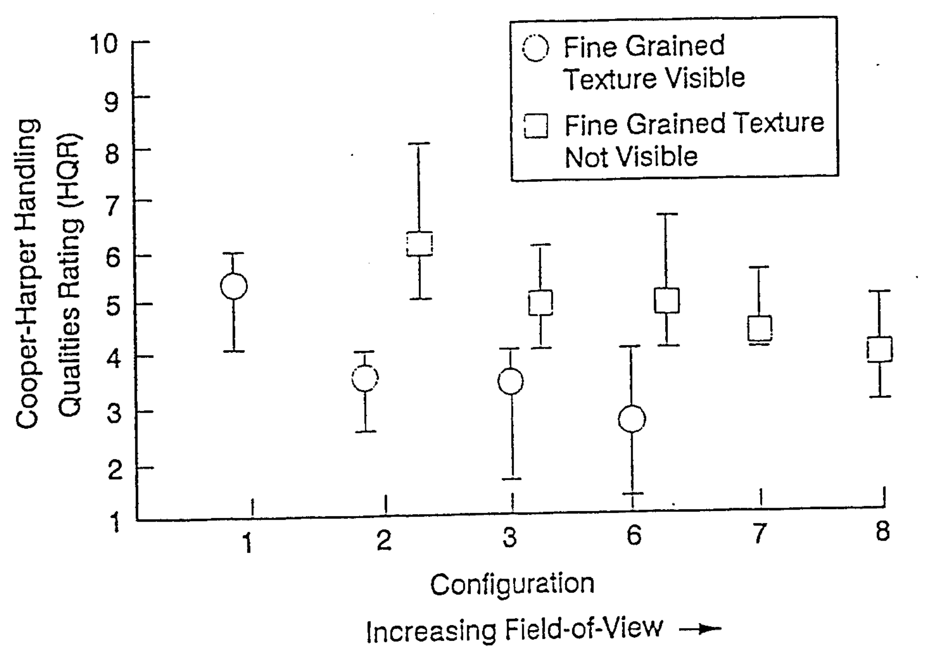
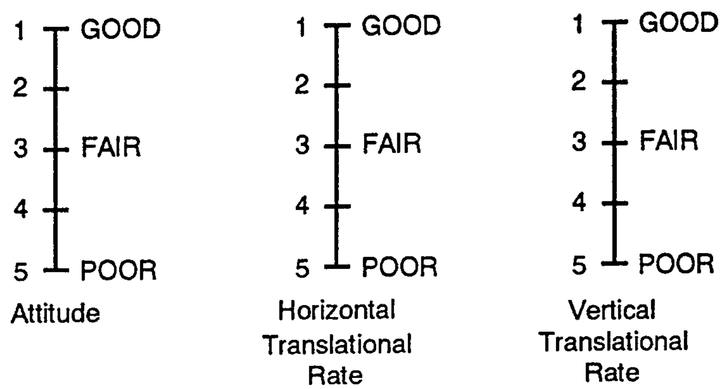


Figure 4. Effect of Field-of-View and Microtexture (Ref. 16)



DEFINITIONS OF CUES

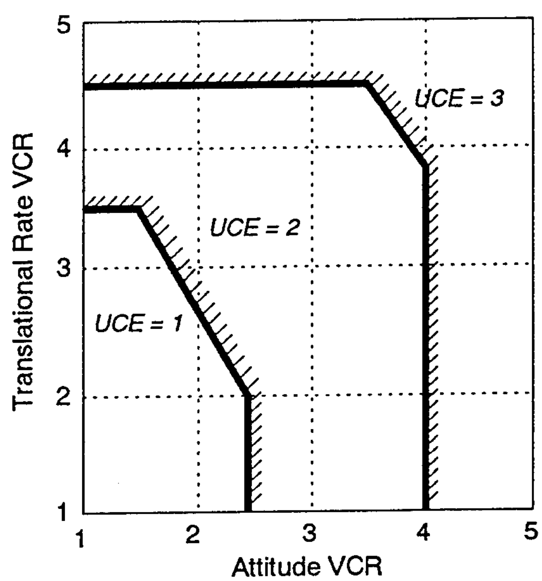
X = Pitch or roll attitude and lateral, longitudinal, or vertical translational rate.

Good X Cues: Can make aggressive and precise X corrections with confidence and precision is good.

Fair X Cues: Can make limited X corrections with confidence and precision is only fair.

Poor X Cues: Only small and gentle corrections in X are possible, and consistent precision is not attainable.

a) Visual Cue Rating (VCR) Scale to be Used When Making UCE Determinations



b) Definition of Usable Cue Environments

Figure 5. Definition of the Usable Cue Environment for Rotorcraft (from Ref. 5)

specification (Ref. 5), shown in Figure 5. These scales are based on the ability of the pilot to maneuver with precision and aggressiveness, *not* on the pilot's perception of the available cuing. This is based on flight testing and ground-based simulation that found that cue environments that appear to be more than adequate from a static viewpoint are often not sufficient to accomplish the task. A common example is the problem of making soft touchdowns on ground-based simulators even though the runway environment seems extremely realistic.

The concepts behind this scale are equally applicable to fixed-wing airplanes, though there are some obvious differences in terms of the detailed requirements due to differing operating conditions. Since the military standard is a handling qualities document and *not* a display design document, the UCE scale is not intended in any way to specify, or even influence, the specifics of the design of cockpit displays. It is, however, a metric by which the display designer can begin to assess the impact of new concepts on the required handling qualities of a proposed aircraft configuration, and vice versa. It is, therefore, a common methodology for communications between handling qualities engineers and display design engineers.

D. CRITERIA FOR ADVANCED, MULTI-MODE FLY-BY-WIRE AIRCRAFT

Some of the features of fly-by-wire (FBW) technology have already been hinted at, especially the capability for creating novel response types. Future generations of advanced FBW designs will reflect more and more capability as the features of FBW are exercised. The performance enhancements obtainable from, for example, statically unstable airframes, will be realized, and the advanced aircraft will routinely operate in performance regions not attainable with analog designs. It will be possible to tailor the control system to every required operational environment, providing automatic flight throughout the flight envelope.

With these features come some obvious drawbacks and potentially devastating problems. For example, the sampling, filtering, and computational requirements introduce undesirable time delays; the possibility for "surprise" responses exists during mode transition and near (or on) software-provided operating performance limits; the great potential for task-tailoring introduces the opportunity to apply nonlinear response dynamics that may not always be desirable. During any operations with automatic flight modes engaged, the pilot's workload may potentially be *higher* because of the requirement to both monitor system performance and perform non-piloting duties.

All of these features and dangers for advanced FBW aircraft must at least be addressed in the mission-oriented MIL Standard. Many of them have too broad an application, or are not sufficiently

mature, to justify specific requirements or criteria. There is, however, a need for discussion of all of these elements in the background document for the MIL Standard. This discussion will serve three major purposes: 1) it will provide guidance for the designer of such control systems in terms of their impact on handling qualities; 2) it will give the handling qualities engineer insight into the advantages and disadvantages of the various concepts; and 3) it will provide a common language between the handling qualities and flight control systems specialists.

E. DEFINITION OF MANEUVER AMPLITUDE

The criteria of MIL-STD-1797A generally fall into one of two categories: 1) criteria for small-angle, closed-loop piloted control, and 2) criteria for large-angle, open-loop control. Examples of small-angle criteria include the CAP, Bandwidth, and Neal-Smith criteria in pitch (all of which are concerned primarily with fine tracking or precise attitude control) and roll mode time constant in roll; examples of large-angle criteria include limit load factor in pitch and time to roll through a specified bank angle (ϕ_t) in roll. There is no specific limitation on the small-angle criteria in MIL-STD-1797A, suggesting that the required level of response (e.g., Bandwidth or short-period frequency) must be maintained throughout the Operational Flight Envelope. MIL-STD-1797A as currently written does not recognize the natural pilot acceptance of lower response bandwidths as maneuver amplitude increases (i.e., as the pilot's concerns shift from *precision* to *aggressiveness*), or the region between fine closed-loop tracking and purely open-loop control (see Table 3).

TABLE 3. HANDLING QUALITIES CRITERIA AS A FUNCTION OF MANEUVER AMPLITUDE

Maneuver Amplitude	Small Amplitude	Moderate Amplitude	Large Amplitude
Piloted Operation	Continuous Closed-Loop Control	Quasi-Open-Loop Pursuit ("Agility")	Open-Loop Control
Handling Qualities Criteria	CAP, Bandwidth, $1/T_R$, etc.	Attitude Quickness	Control Power, ϕ_t , etc.

The mission-oriented standard must account for all maneuver amplitudes. The region between fine tracking and pure large-amplitude control may involve quasi-open-loop operation by the pilot requiring, for example, a rapid turn to gain firing advantage in air combat. Hence, it entails some aspects of control power (how *quickly* the aircraft banks) and bandwidth (how *precisely* the pilot can attain the new bank angle). The time-to-bank requirements specify only time to *achieve* a bank angle change, with no requirements on *stopping* there. This region of moderate-amplitude, quasi-open-loop maneuvering is the

subject of most recent studies of aircraft agility (though there is no consensus on what agility *is*, Ref. 18). Most agility criteria suffer from a sensitivity to the pilot's ability to achieve a final attitude within some tolerance; despite this, the mission-oriented MIL Standard must account for moderate-amplitude maneuvering requirements by incorporating a set of criteria based on agility.

A prime candidate criterion was developed for the rotorcraft specification (Ref. 5) that does not have the shortcomings of most proposed agility metrics. Development of Level boundaries for the "attitude quickness" criterion, defined in Figure 6, will require the generation of new data.

F. DEMONSTRATION MANEUVERS

While the goal of any handling qualities document is to assure satisfactory handling qualities, it is impossible to guarantee this simply by requiring compliance with a set of specific, narrow criteria — i.e., it is always possible to meet each of the criteria but still have an unacceptable article. The only final proof of handling is in flight testing the vehicle itself for actual mission maneuvers. Therefore a minimum number of "demonstration maneuvers" is needed as an integral part of the standard, including well-defined requirements for desired and adequate performance (as interpreted for Handling Qualities Ratings). The rotorcraft specification (Ref. 5), as an example, contains a total of 21 maneuvers to be conducted in both good and degraded visual conditions. The procuring activity may, at its discretion, require the final article to show satisfactory (Level 1) handling qualities for one or more of these maneuvers *in addition to, and not in place of*, the conventional analytical requirements. This is very important, because any specified demonstration maneuvers should be viewed as a supplement to the analytical requirements, and not as a replacement.

A minimum set of demonstration maneuvers will be required for the mission-oriented standard; definition of performance requirements must be done with great care, and preferably with the assistance of members of industry and government.

BASED ON OPEN LOOP BOXCAR INPUTS OF VARYING DURATION AND AMPLITUDE.

IS ANALOGOUS TO BANDWIDTH, EXCEPT IT APPLIES TO LARGER AMPLITUDE MANEUVERS.

DEFINITION OF CRITERION PARAMETERS, AND EXPECTED SHAPE OF BOUNDARIES IS SHOWN BELOW.

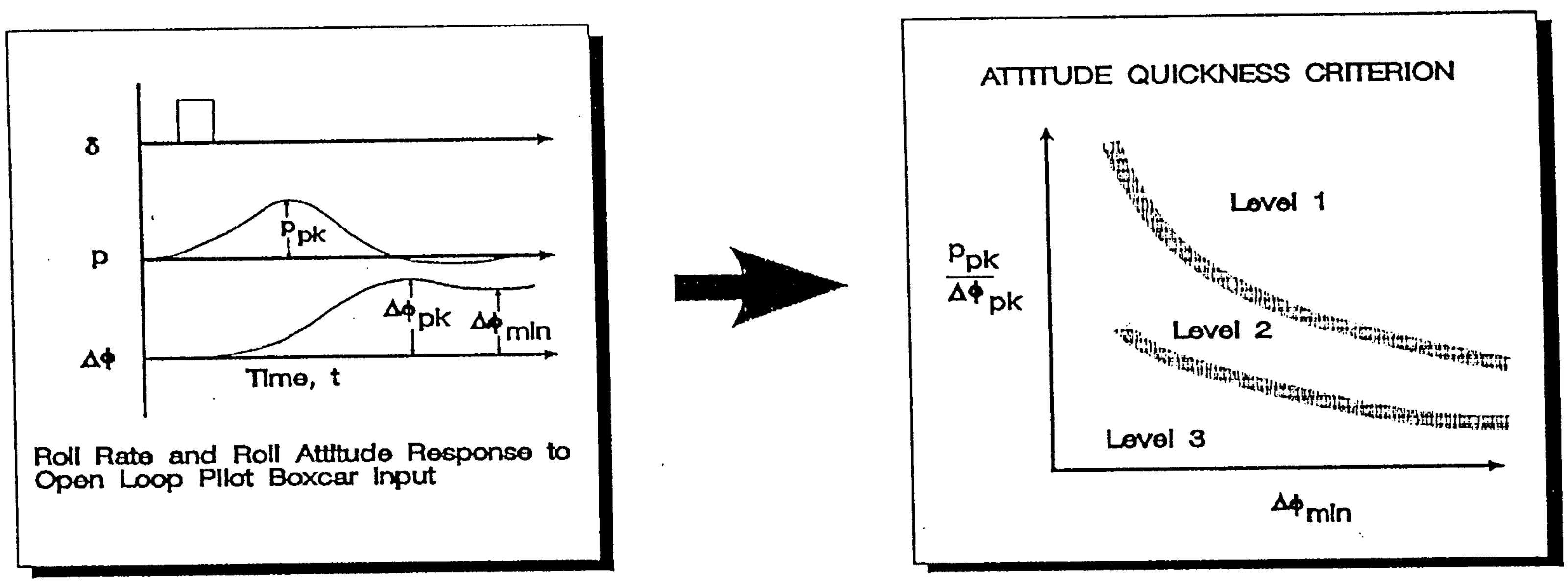


Figure 6. Attitude Quickness Criterion as a Moderate Amplitude Agility Requirement

SECTION IV

EFFECTS OF FEEL SYSTEM DYNAMICS ON FLYING QUALITIES

A. BACKGROUND

There is a continuing controversy over the importance of the cockpit control feel system on the pilot's assessment of airplane flying qualities. Because this controversy exists — and especially because it can have significant impact on the military specification — this section of the report is devoted to a review of this subject. Portions of this discussion are based on Ref. 19.

While it has long been recognized that the dynamics of the cockpit feel system are important to the pilot, the impact of such dynamics on the pilot's perceptions of flying qualities is not well understood. A logical question has been: should the cockpit manipulator's feel-system characteristics be considered an element of the airplane?

In the writing of the draft version of the military standard (Ref. 10), the authors reviewed the data available to date and, following several meetings with flying-qualities experts, decided that the important reference for flying qualities purposes was control *force*.

Before the release of the Air Force's standard, MIL-STD-1797(USAF) (Ref. 20), in 1987, the flight experiment of Ref. 21 was performed. These quantitative data, in combination with experiences with force-sensing controllers on the X-29 and F-18, suggested that the impact of the feel system on pilot opinion may be overrated. This evidence raised sufficient questions so that for the equivalent-system requirements of MIL-STD-1797(USAF) both force and position inputs were required. The final document, MIL-STD-1797A (Ref. 1), is unchanged in this regard. Unfortunately, as we will see, the requirements of the military standard are mixed in their dealings with the cockpit feel system.

Recent concerns about pilot-induced oscillations (PIOs) have caused these questions about the impact of the feel system to resurface. Because the questions continue to linger, this section of the report will provide a brief review of data that suggest that, rather than ignoring the feel system, or including it only at times, it is most appropriate to *always* include the dynamics of the cockpit feel system as a part of the total aircraft model. Implications on MIL-STD-1797A are discussed as well.

B. DEFINITIONS

Aircraft command systems are either force or position sensing, as sketched in Figure 7. For position (or displacement or deflection) sensing, Figure 7a, the reference point for handling qualities measurements

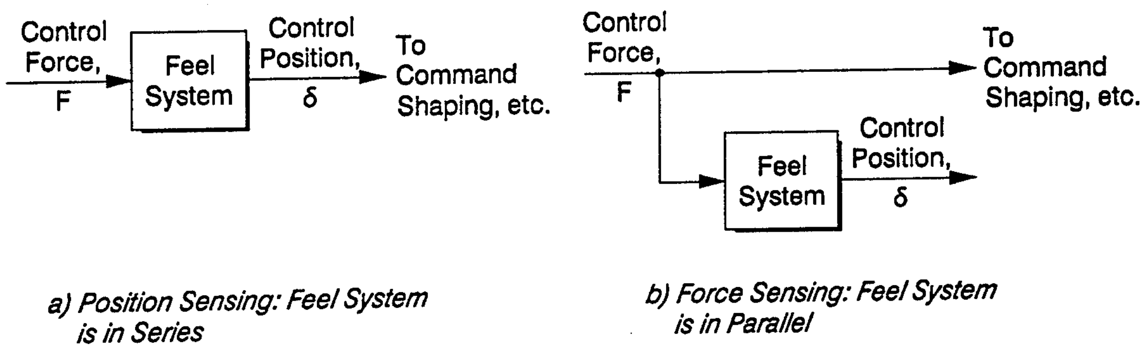


Figure 7. Mechanization of Feel Systems

is very important: all measurements in terms of position do not include the feel-system dynamics, while measurements from force do. For force-sensing controllers, Figure 7b, the feel system is in parallel for force reference and downstream of the position reference point, and therefore is not included in either case.

The issue of what to do with the feel system revolves around philosophies of the pilot's actions in controlling the aircraft: does the pilot sense and respond to control *displacements* or control *forces*? The governing equation relating stick force, F, and position, x, is:

$$F = I\ddot{x} + b\dot{x} + kx$$

where I is the stick inertia, b is the damping, and k is the spring gradient. Dividing by I, we see that damping and frequency of the resulting second-order dynamic system are given by:

$$2\zeta_{FS}\omega_{FS} = b/I \text{ and } \omega^2_{FS} = k/I$$

or

$$\zeta_{FS} = b/\sqrt{4Ik},\ \omega_{FS} = \sqrt{k/I}$$

Ideally, we should be able to place flying qualities requirements on the damping and frequency of the feel system. Unfortunately, the current data base is not sufficient to allow this at this time.

C. THE FEEL SYSTEM AND MIL-STD-1797A

In general, the requirements of MIL-STD-1797A specify that the feel system be excluded from the dynamics of the aircraft. As evidence of this, Table 4 summarizes the key pitch, roll, and yaw dynamic requirements and how each of them addresses the feel system. Only the pitch equivalent-systems requirements based on CAP specify that the feel system be considered, and in this case analysis is to be

TABLE 4. HOW THE DYNAMIC REQUIREMENTS IN MIL-STD-1797A DEAL WITH THE COCKPIT CONTROL FEEL SYSTEM

REQUIREMENT	APPLICATION OF REQUIREMENT	INCLUDE OR EXCLUDE FEEL SYSTEM?
4.2.1.2 Short term pitch response	**A. CAP or $\omega^2_{sp}/(n/\alpha)$, ζ_{sp}:** "requirements apply to the equivalent-system parameters determined from the best match for force inputs, and also for deflection inputs"	**BOTH**
	Equivalent pitch time delay, τ_θ: "apply to the value for $\theta(s)/\delta_{es}(s)$ for a deflection control system... and to $\theta(s)/F_{es}(s)$ for a force control system"	**EXCLUDE**
	B. $\omega_{sp}T_{\theta_2}$, ζ_{sp}, τ_θ: Same as above	**BOTH**
	C. Transient peak ratio, rise time: "response to a step input of pitch controller force, and also to a step controller deflection"	**BOTH**
	Effective delay: "step controller deflection for a deflection control system... and the step controller force for a force control system"	**EXCLUDE**
	D. Bandwidth, Time Delay: "response to pilot control force for force controllers... and to pilot controller deflection for deflection controllers"	**EXCLUDE**
	E. Closed-Loop Criterion [Neal-Smith]: "The pilot output is force for force controllers... and deflection for deflection controllers"	**EXCLUDE**
	F. Time- and frequency-response criteria by Gibson: Not stated either way (some figures show force, some show deflection)	**UNKNOWN**
4.5.1.1 Roll mode	"Use δ for deflection control systems... and F for force control systems"	**EXCLUDE**
4.5.1.5 Roll time delay	Obtain equivalent time delay from applying 4.5.1.1	**EXCLUDE**
4.6.1.1 Dynamic lateral-directional response	"Use δ_{as} for deflection controls... and F_{as} for force controls"	**EXCLUDE**

performed both with and without the feel system. In some cases, this is in direct conflict with the basic intent and development of the criteria. For example, the pitch attitude Bandwidth requirements were developed entirely based on force control reference; the flying qualities Levels were drawn on this basis; and the intent was for the reference to always be control force (as defined in Ref. 10). If control position is used for a deflection control system, as specified by MIL-STD-1797A (Table 4), the wrong answer will result.

Table 4 simply confirms the philosophy of the military standard, stated above: based on the Ref. 21 flight research and limited practical experience, assume the feel system is transparent to the pilot, i.e., that it does not influence flying qualities.

D. THE FEEL SYSTEM IS NOT TRANSPARENT TO THE PILOT

There is a school of thought in the flying qualities community that the feel system, *when well designed*, is transparent to the pilot. Since every airplane ever built has had some form of feel system, whether it is aerodynamic or hydraulically boosted, a similar argument might be made that *the feel system is a constant across all airplanes: it is always there*. Therefore, why address it in the specification?

Unfortunately, we do not have a good grasp, at this time, on what a "well designed" feel system is. In the absence of a flying-qualities requirement, there is simply no way for an airplane manufacturer to be certain, throughout the design and development process, that the feel system will not cause some degradation in flying qualities when the final article is built. And as long as there are no specific requirements, the manufacturer is given the freedom of totally ignoring the possible adverse impact of the feel system on flying qualities, simply because he is told that it is "transparent to the pilot."

On the other hand, we are fortunate that most, if not all, of the flight research data upon which the requirements of MIL-STD-1797A are based were generated with variable-stability airplanes equipped with feel systems that were, indeed, well-designed. In other words, the impact of including or excluding the feel system dynamics on these flight data will probably not change the story significantly.

There is clear evidence that the feel system is *not* transparent to the pilot. The feel system impacts both pilot dynamics and the pilot's assessment of flying qualities. As is shown below, the degree of this impact varies among pilots and tasks.

1. Impact on Pilot Dynamics

The best evidence of the effects of the feel system on pilot dynamics comes from a number of ground simulation and flight experiments. In these experiments the subjects performed compensatory tracking (see Ref. 22), responding to displayed errors and attempting to null the errors with varying forms of controlled element dynamics. For any one controlled element, the effects of the feel system can be tracked by observing the change in pilot-vehicle crossover frequency, ω_c, as the feel system changes. If the feel system is truly transparent to the pilot, crossover frequency should be invariant with feel system frequency. For this analysis we will use k/s (or near-k/s) controlled element dynamics.

In the study of Ref. 23 a fixed-base simulation was performed with roll error displayed on an oscilloscope. The manipulator consisted of a pencil-like stick (actually a control stick for a radio-controlled airplane) for which "The damping and inertia were made as low as possible." The stick had only a centering spring with a gradient of 2.2 oz/deg. Total deflection, on a 4-in. moment arm, required only 2 lb force and the natural frequency of this system was near infinity. Hence the pilots in this experiment were effectively flying a scope with a pencil. The crossover frequency achieved with k/s dynamics was around 4.6 rad/sec. This is plotted in Figure 8.

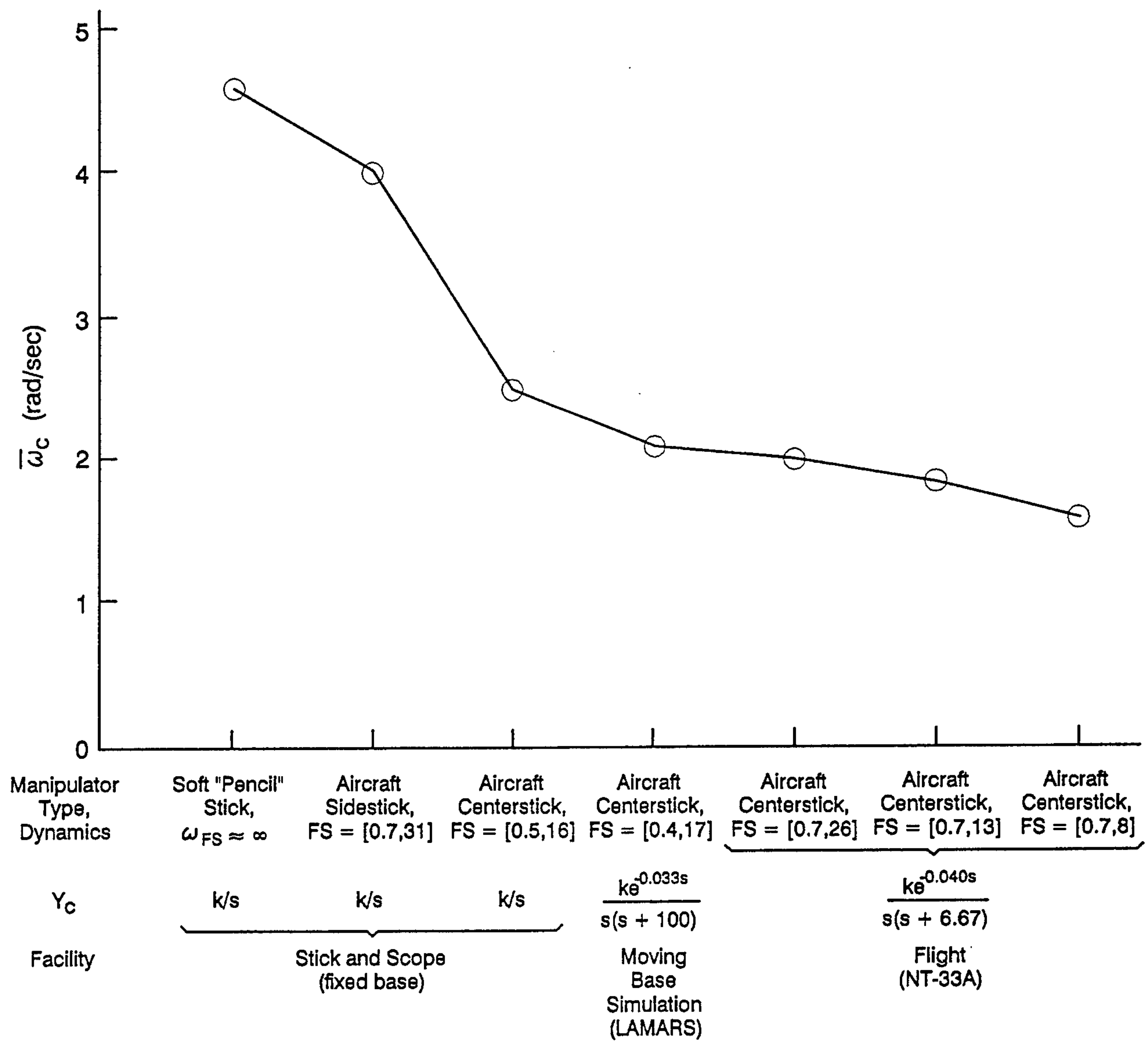


Figure 8. Effect of Manipulator and Facility on Crossover Frequency for Roll Sum-of-Sines Tracking with k/s-Like Vehicle Dynamics (Connecting Lines Shown for Clarity Only)

In Ref. 24, a simulation setup similar to that in Ref. 23 was used to evaluate the effects of stick characteristics in roll tracking. The primary difference from the Ref. 23 study was use of an airplane-like sidestick controller instead of the pencil stick. Stick dynamics were provided by a McFadden force loader system; several different sets of stick dynamics were evaluated. The crossover frequency for the stiffest stick, with feel system frequency ω_{FS} = 31.4 rad/sec, was approximately 4 rad/sec (Figure 8), or about 1/2 rad/sec lower than the Ref. 23 value.

In the Minimum Flying Qualities study of Ref. 25, sum-of-sines tracking was performed in both pitch and roll using the stick-and-scope setup and in the LAMARS motion-base simulator at Wright-Patterson AFB. In both cases a centerstick was used. In the fixed-base portion of the study, the stick feel system natural frequency was 16 rad/sec, about half that of Ref. 24, and the average crossover frequency in roll for k/s was 2.5 rad/sec. This is considerably lower than the 4 rad/sec found in Ref. 24 or 4.6 from Ref. 23; it is assumed that the reasons for this difference are the slower stick feel system (which is part of the effective controlled element as seen by the pilot) and the centerstick (which requires larger displacements than the sidestick and hence either higher initial accelerations or higher control sensitivity to achieve the same roll response per degree of angular stick deflection).

In the LAMARS simulation portion of Ref. 25, it was impossible to attain perfect k/s controlled element dynamics because of the lags of the digital computer. In addition to k/s, the controlled element had a first-order lag at 100 rad/sec and digital delays that, lumped together, introduced about 0.033 sec of overall time delay. The motion system of the LAMARS, obviously, also contributed some lag to the motion sensed by the pilot. In this experiment the average crossover frequency drops again, to about 2.1 rad/sec. It is possible that the additional delays and lags caused this drop in ω_c; certainly, pilot sensing of motion may have been a factor as well. It might be expected that the addition of motion cues would increase the effective crossover frequency, since the pilot now has one more sensory feedback. It is possible, however, that motion served the opposite effect, i.e., the motion cues provided the pilot with a more direct sense of the absolute magnitude and frequency of his control inputs, and, since large and sharp inputs would be uncomfortable, the pilot may have backed off at times as a result.

In the feel system study of Ref. 26, Calspan flew sum-of-sines roll tracking tasks on the NT-33A airplane. The describing function data, documented in great detail in Ref. 19, show that with the best roll damping (inverse time constant, $1/T_R$ = 6.67 rad/sec) and highest feel-system frequency of 26 rad/sec, a crossover frequency of around 2 rad/sec was achieved, or near the LAMARS value. There is evidence of still lower crossover frequencies as the feel-system frequency is reduced; the data scatter was

considerable, however, and the data plotted in Figure 8 represent the best, rather than average, crossover frequencies.

From Figure 8 it is clear that, in a dynamical sense, the feel system is far from transparent to the pilot. It does not, however, provide any indication of the impact of the feel system on the pilot's assessment of flying qualities.

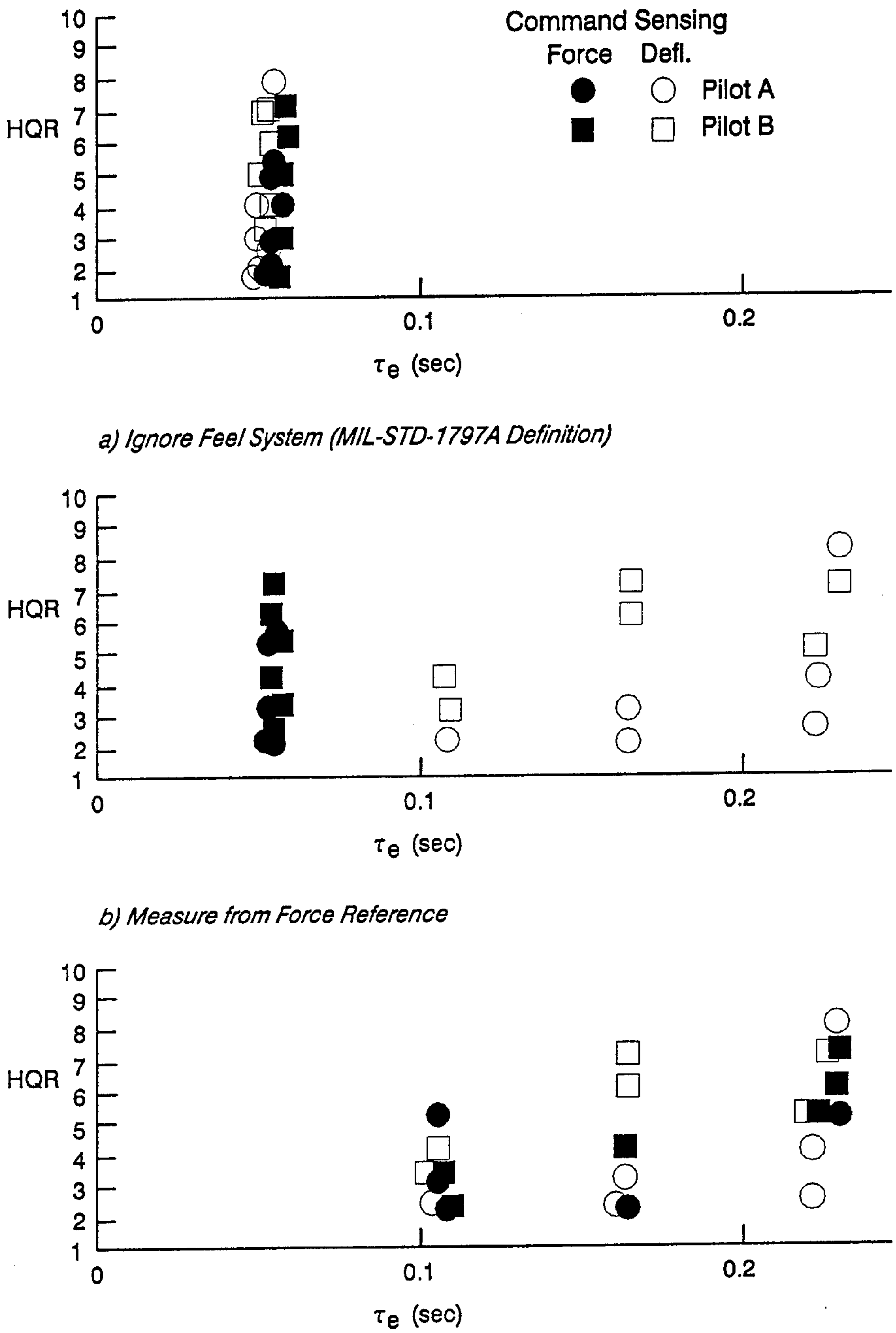
2. Impact on Pilot Opinion

In the one-flight NASA experiment of Ref. 21, Smith and Sarrafian found that the effects on handling qualities of the feel system were not equivalent to the effects of an added pure time delay. The researchers concluded that the feel system is a unique dynamic element that is not addressed by time-delay requirements in the military specifications.

The follow-on study (Ref. 26) performed by Calspan using the variable-stability NT-33A had a greatly expanded matrix of configurations, tasks, and pilots. The results of this study do not directly refute the conclusions drawn by Smith and Sarrafian. Instead, they augment the observation that the feel system is a unique dynamic element and does not impact handling qualities to the extent of an equivalent time delay. A subsequent analysis (Ref. 19) of the Calspan data supported these conclusions. On the other hand, these data do suggest that the pilots were aware of changes in the feel system, and that, in terms of pilot *ratings*, the effects were similar to those caused by an equivalent level of added time delay.

As evidence of the effect of feel system frequency on pilot ratings, Figure 9 shows a subset of the data from the Calspan experiment. The HQRs are for the precision offset landing task, for those configurations flown with both force and position command sensing. Three pilots participated in this study, but the ratings for only two of the pilots are shown here, for reasons explained in Ref. 19. The only variations in the configurations shown are the frequency of the feel system, ω_{FS}, and the command sensing, force or position. The ratings have been plotted against equivalent time delay. (It is important to recognize that much of this data shows considerable apparent scatter that may be due in part to different values of control sensitivity.)

If the feel system were entirely transparent to the pilot, there should be no evidence of a variation in HQR with feel system frequency. This is the same as using position reference for all of the cases, as specified by MIL-STD-1797A. As Figure 9a indicates, the result is a scattering of ratings from 1.5 to 8 at an equivalent time delay of about 0.05 sec (this delay results from filters and the actuator lags).



a) Ignore Feel System (MIL-STD-1797A Definition)

b) Measure from Force Reference

c) Always Include Feel System

Figure 9. Effects of Feel System Frequency, Landing (All Cases Flown with Both Force and Position Sensing)

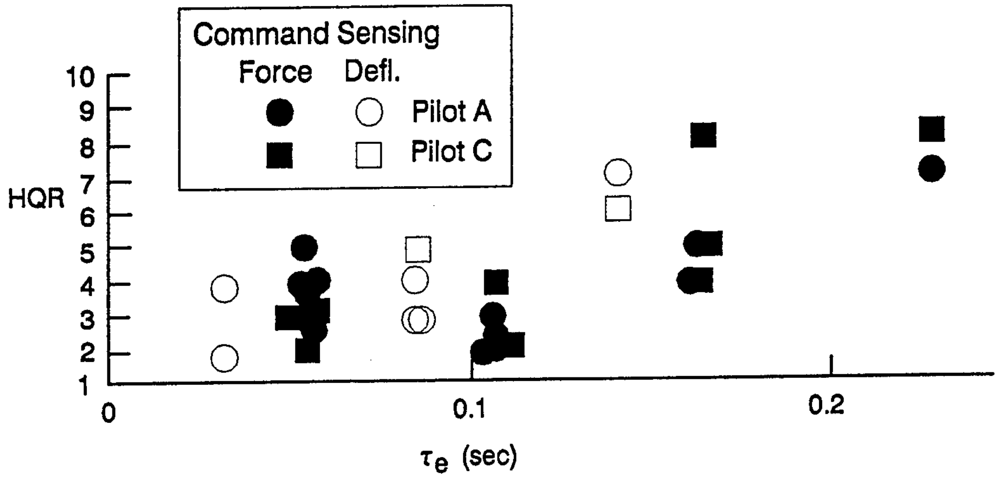
If the data were referenced to force, the feel system is included for the position-sensing cases (open symbols), and there is a degradation in HQR with decrease in feel system frequency (Figure 9b). There continues to be a scatter of ratings from 2 to 7 with zero delay, however. These are the force-sensing cases, where the feel system is not picked up in the force reference. There is also evidence of scatter for the position-sensing cases: pilot C shows a degradation in ratings as feel system frequency is decreased, while Pilot A does sometimes, but does not at other times. It is significant that Pilot A shows a general insensitivity to changes in feel system dynamics, since this is the same pilot from Ref. 21, where a similar lack of correlation was found. In Ref. 19 these ratings by Pilot A are considered to be an enigma because they are not consistent with pilot C's ratings, and they are also not consistent with pilot A's ratings for up-and-away tasks, where both pilots show similar degradations in ratings with feel system frequency. Yet pilot A is clearly consistent between experiments, since the data of Refs. 21 and 26 show the same effects.

Finally, if it is assumed that the feel system is *always* a factor in the pilot's opinions, and is therefore included for all cases, the ratings for the force-sensing cases lie close to those for position sensing (Figure 9c).

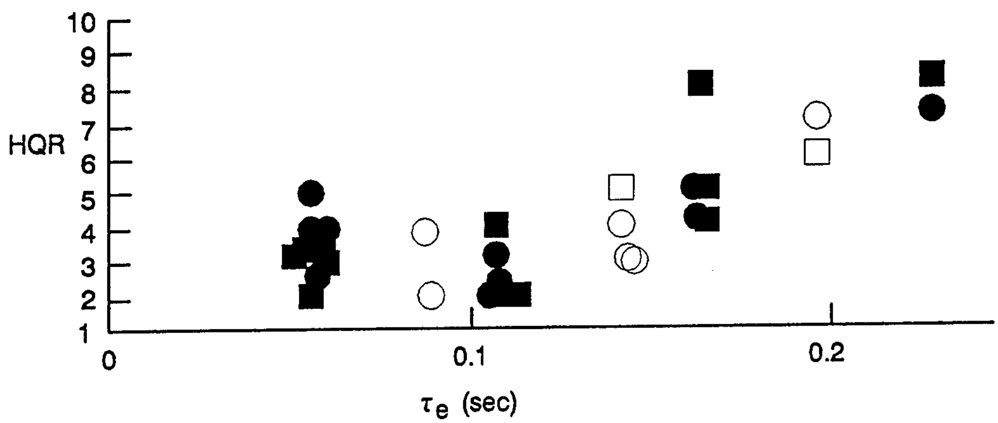
Figure 9 is evidence that 1) the pilots can be sensitive to the effects of the feel system, 2) the command sensing type does not make a large difference on pilot ratings, and 3) the effects of the feel system can be different for different pilots and different tasks. Conservatively, the ratings of pilot C should be given the most weight when flying qualities requirements are developed. Certainly these data are not overwhelming evidence of the importance of the feel system on pilot ratings.

The impact of the Figure 9 data is enhanced when they are compared with the ratings from another subset of the Ref. 26 study: those cases where the feel system dynamics were good, and time delay was added to the aircraft. Figure 10 shows these ratings. Whether the feel system is ignored, included only for position sensing, or included for all cases, the data in Figure 10 show similar trends. There is still considerable pilot rating scatter at any one value of equivalent time delay, but the best overall agreement appears to be for Figure 10b, where the feel system is included only for position sensing. Still, if the data of Figures 9c and 10c are compared, the range of pilot ratings, and change in ratings with equivalent time delay, are quite similar. This suggests that *the effects of the feel system on pilot ratings may be similar to the effects of added time delay.* Evidence of this is actually presented throughout the discussions of Section V of this report.

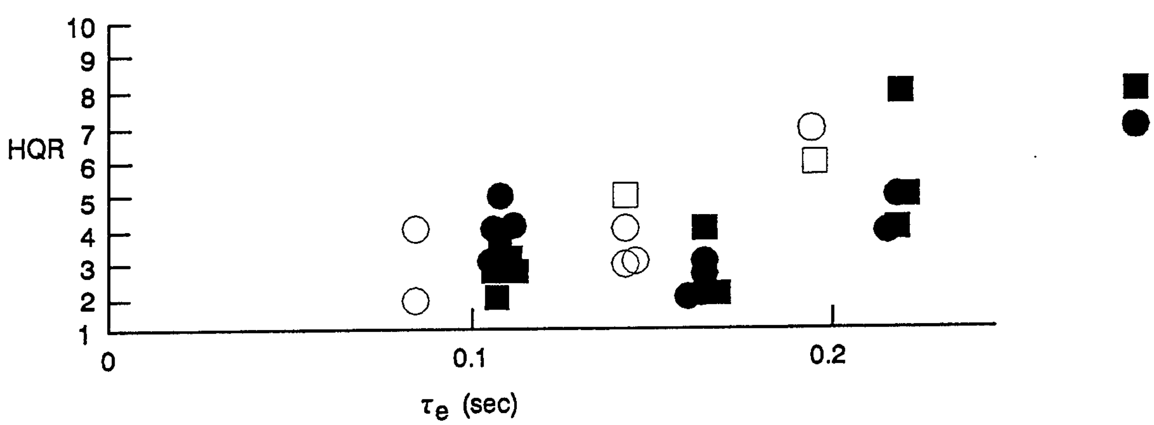
Some researchers have concluded that the feel system should not be included in calculating parameters for certain criteria, based primarily on empirical observations. That is, the data fit the criterion



a) Ignore Feel System (MIL-STD-1797A Definition)



b) Measure from Force Reference



c) Always Include Feel System

Figure 10. Effects of Added Delay on Equivalent Time Delay with Fast Feel System, Landing (All Cases Flown with Added Time Delay)

boundaries better if the feel system is ignored. This result is in conflict with the analysis discussed above, and suggests that pilots *always* override the feel system lags. It is more likely that the criterion boundaries need to be refined. Given that the requirements of MIL-STD-1797A specify that the feel system be either excluded or both included and excluded, this change in philosophy says that a review of all of these requirements may be in order.

E. HOW THE FEEL SYSTEM HAS BEEN HANDLED IN THIS REPORT

Based on the data presented here and elsewhere in this report, it is clear to the authors that the feel system *is* a factor in the pilot's assessment of flying qualities, and hence affects pilot ratings. It is also clear from the data of Ref. 26, augmented by the results of helicopter experiments reported in Refs. 27 and 28, that the effects of the feel system need to be accounted for, either separately or as a part of the flying qualities requirements of MIL-STD-1797A.

Because it is difficult, even for the data of Ref. 26, to separate out the effects of the feel system from the effects of other parts of the airplane, it is recommended that, until more data become available, the requirements of MIL-STD-1797A be specified to always include the effects of the feel system. This has been the approach adopted in this report.

SECTION V

DETAILED REVIEW OF REQUIREMENTS

A. INTRODUCTION

A number of the paragraphs in the flying qualities military standard must be revised to reflect the mission-oriented structure outlined in this report. In addition, several of the quantitative requirements may be considered candidates for revision based upon recent experimental data. Following is a detailed review of those paragraphs considered for revision. This review takes three forms. First are those requirements requiring modification only, to incorporate the mission-oriented structure, with no significant changes otherwise. Second, for those requirements in the 1990 release of MIL-STD-1797A (Ref. 1) that were analyzed extensively, recommended changes to the requirements and their supporting data, if applicable, are given. Third are those requirements that are entirely new to the military standard, developed either from existing data (such as the flightpath Bandwidth requirements) or from the data generated in the simulation performed for this contract (see Appendix A).

Every effort has been made to follow the format of MIL-STD-1797A. When the discussion for a particular paragraph would become too unwieldy for this format (e.g., whenever the review consists only of comments and not revised or entirely new requirements), only general discussion is presented. Recommended changes or additions to requirements in the current standard are printed in *italics*. (Remember that, in the following, the section numbers are referenced to the *Standard*, because it is the legal document, but the focus of the discussions is on the contents of *Appendix A* of the Standard, "Flying Qualities of Piloted Aircraft, Handbook for," because that is where the real requirements reside.)

Because this is a rather lengthy section, the numbering system for figures and tables has changed. Rather than follow numerically from the previous section, each figure and table will show the relevant MIL-STD-1797A paragraph number (or proposed paragraph number) parenthetically, and each new paragraph will start with new numbers (Figure 1(4.2.1.2), etc.). While this is not normal convention for a technical report, it is felt that it makes the association between text, figures, and tables much easier to follow.

B. DETAILED REVIEW OF REQUIREMENTS

1.0 SCOPE

2.0 APPLICABLE DOCUMENTS

DISCUSSION

No specific changes are recommended to these sections. Section 2, obviously, will require extensive updating to reflect the results of the last decade's work in flying qualities.

3.0 DEFINITIONS

3.1 Aircraft classification and operational missions

DISCUSSION

There are no specific changes recommended for this requirement. Ideally, the references to aircraft weight would be eliminated, since it is the aircraft's mission, and not its weight, that should matter. An example of this is the C-17, which might technically be a Class III airplane because it is a "large, heavy" transport. The STOL landing requirements of the C-17, however, are more closely aligned with those defined for the stringent landing task for Class IV than with those of Class III. It is recommended that the discussion under Requirement Guidance be augmented to point out the importance of mission as opposed to weight. In the example of the C-17, evidence suggests that it may have been more appropriate to consider it to be a Class IV airplane ("highly maneuverable") for landing, but Class III for most other tasks. Similarly, the precision required to perform low-altitude parachute extraction (LAPES) testing may be beyond that normally associated with Class III airplanes.

In a thoroughly mission-oriented flying qualities specification, aircraft Class would not appear at all, but would be inferred by the specific Mission Task Elements to be applied. For example, if precision tracking is not required for a particular new airplane, it is irrelevant whether the airplane is to be a light trainer or a heavy transport. Requirements that emphasize maneuverability, such as the time-to-bank requirements, may be more of a challenge; but again, whether high maneuverability is required or not, aircraft mission, not size, should be the determinant.

3.2 Flight Phase Categories

DISCUSSION

This is an area of significant change for the military standard, as the Flight Phase Categories of MIL-STD-1797A are replaced by mission-oriented task elements. The rationale for this change is discussed in detail in Section III of this report. The requirement under 3.2 should be replaced in its entirety with the new Categories and Mission Task Elements introduced in Section III.

3.3 Levels and qualitative suitability of flying qualities

DISCUSSION

The military standard does not directly apply the Cooper-Harper scale to the quantitative requirements. The reasons for this are outlined in the Requirement Guidance for this paragraph. Yet every quantitative criterion in the specification was developed using pilot ratings. In the Army's rotorcraft specification ADS-33C, the HQR scale is used explicitly to define flying qualities Levels, consistent with the way the Levels are derived in the first place. It is recommended that a more direct tie be made between the requirements and the HQR scale. In the modern era it has become clear that pilots and engineers are more familiar with the words on the Cooper-Harper scale than with the words defining "Satisfactory," "Acceptable," and "Controllable." In fact, a commonly noted contradiction is the use of the word "adequate" to define Satisfactory. Aircraft that are adequate are normally considered to be in the range of 4 to 6 on the HQR scale (i.e., aircraft for which "adequate performance [is] attainable with a tolerable pilot workload").

Following is the definition of Levels from the currently proposed military standard for rotorcraft handling qualities (Ref. 6):

> **Levels of handling qualities.** Handling qualities depend on the aircraft's flying characteristics, the piloting task being performed, the usable cue environment, wind and turbulence, and any additional demands on the pilot. Levels of handling qualities are defined by the 1 to 3, 4 to 6, and 7 to 8 ranges of the Cooper-Harper Handling Qualities Rating (HQR) Scale. This specification uses two distinct methods of establishing Levels of handling qualities.
>
> **a. Predicted Levels based on flying qualities parameters.** The first method consists of comparisons with quantitative boundaries of flying qualities parameters. When establishing compliance, the rotorcraft's flying qualities parameters shall be determined and compared with the boundaries appropriate to the rotorcraft's operational requirements. A Level 1 rotorcraft must meet the Level 1 standards for all of the criteria. Violation of any one

requirement is expected to degrade handling qualities. Violation of several individual requirements (e.g., to Level 2) could have a synergistic effect so that, overall, the handling qualities degrade to Level 3, or worse. The quantitative criteria are based on previous experiments and analyses, and hence result in predicted Levels of handling qualities.

b. **Assigned Levels based on flight test maneuvers.** The second method of establishing Levels is to perform a set of well-defined flight test maneuvers using a team of at least three pilots. These pilots assign HQRs to the aircraft for each maneuver, The average HQR determines the Level for each maneuver and a Level 1 rotorcraft must be rated Level 1 for all of the maneuvers designated as appropriate to the aircraft's operational requirements. Compliance with the flight test maneuvers is based on piloted evaluations, and therefore results in assigned Levels of handling qualities.

The quantitative criteria are based on HQR data from engineering in-flight and ground-based simulation. This knowledge is not complete; data are not available to fully define the required limits for all flying qualities parameters which taken together will ensure good handling qualities for all mission tasks. Thus the predicted handling qualities could be in error. Similarly, the flight test maneuvers are not sufficiently comprehensive to represent all mission maneuvers in all environments that a particular aircraft may be called upon to perform. Comparisons with both the quantitative criteria and the flight test maneuvers are necessary to maximize the likelihood of an accurate assessment of the Level of handling qualities. If there are conflicts between the predicted and assigned Level, the quantitative criteria and the flight test maneuver procedures should be scrutinized to determine the cause of the discrepancy. On the basis of this investigation, the Government will determine whether or not compliance has been achieved or if further testing is required.

If the Cooper-Harper scale is adopted to directly define Levels, some of the definition for "Controllable" will still be required, to make it clear that Level 3 includes the ability to transition from aggressive flight phases to non-aggressive flight phases to provide a "get-home" capability.

4.0 REQUIREMENTS

4.1.4 Flight Envelopes

DISCUSSION

The only changes recommended are in the discussions for the Flight Envelopes: updating will be necessary to reflect the new MTES and the regrouping of the existing MTEs. This will especially impact Table I of MIL-STD-1797A (and Table VII of Appendix A in the standard), where Operational Flight Envelope values must be defined for the new MTEs.

4.1.10 Interpretation of quantitative requirements

DISCUSSION

The Requirement Guidance for this paragraph deals almost entirely with the use of equivalent systems. The discussion should be expanded to include some of the caveats now known about equivalent systems. For example, we know that equivalent-systems techniques should never be applied to an airplane with attitude-command dynamics.

The MIL-STD-1797A LOES-based pitch requirements (CAP vs. ζ_{sp}, τ_e) require a special case of equivalent system that uses the classical airplane response type as a lower-order model (see Figure 3 in Section II). Hence it implicitly assumes that the shape of the response is that of a classical airplane. The fitting routine adjusts the equivalent short period and phugoid frequency and damping to fit this model. Any phase lag that is left over is accounted for by the equivalent time delay τ_e. If the basic response does not look like a classical response type (i.e., if the Bode plot does not look like a "Conventional" airplane), it is simply not correct to fit the higher order system to this model. The use of angle-of-attack feedback to augment the short period typically results in a classical response type. Inertial feedbacks, such as pitch rate and pitch attitude, result in non-classical response shapes such as the rate command/attitude hold (RCAH) and attitude command/attitude hold (ACAH) response types in Figure 3, Section II. Comparison of the response type shapes clearly shows that it is not appropriate to attempt to fit the RCAH and ACAH shapes to the Conventional airplane shape. Unfortunately, this mistake continues to be made.

As an aside, note that the general concept of lower order equivalent systems is valid for all response types. Incorporating this type of criteria would require the development of a database for each lower order type (i.e., RCAH, ACAH, etc.) to develop generalized criteria. The RCAH and ACAH Bode asymptotes shown in Figure 3 of Section II would be the obvious choices for the LOES models for these response types. In the context that the Bandwidth criteria apply to the short term response of all response types, however, it does not seem necessary to accomplish the considerable work and experimentation required to develop lower-order models for every conceivable response type.

4.2 Flying qualities requirements for the pitch axis

4.2.1 Pitch attitude dynamic response to pitch controller

4.2.1.1 Long-term pitch response *(phugoid)*

No change is recommended for the specific limits or format for this requirement. This requirement is aimed at the classical phugoid mode, and while it may be possible with advanced control laws to produce modes that have only some of the characteristics of the phugoid, it is still relatively specific to the speed mode of the airplane. To clarify this for the user, add *(phugoid)* to the title.

4.2.1.2 Short-term, *small-amplitude* pitch response

1. RECOMMENDED REQUIREMENTS

4.2.1.2 Short-term, *small-amplitude* pitch response. *The requirements of 4.2.1.2.1 and 4.2.1.2.3 apply to all response types. If it can be demonstrated that the response meets the definitions for a conventional response type, the requirement of 4.2.1.2.2 may be substituted for 4.2.1.2.1. The dynamics of the cockpit pitch control feel system shall be included in all measurements, regardless of command sensing type.*

4.2.1.2.1 Response requirement for all response types (Bandwidth). *The pitch attitude response to longitudinal control inputs shall meet the limits specified in Figure 1. The Bandwidth (ω_{BW_θ}) and phase delay ($\tau_{p\theta}$) parameters are obtained from frequency responses as defined in Figure 2.*

4.2.1.2.2 Alternative requirement for conventional response types (CAP). *The equivalent parameters describing the responses of pitch rate and normal load factor (at the center of rotation) to a pitch control input shall have the following characteristics.*

a. The Control Anticipation Parameter, CAP, defined as $\omega_{sp}^2/(n/\alpha)$, shall meet the limits specified in Figure 3 as a function of short-period damping ratio, ζ_{sp}.

b. The allowable response delay, τ_e, shall be less than the limits specified in Table 1.

4.2.1.2.3 Limits on pitch rate overshoot and pitch attitude dropback. *For response types defined as rate or conventional, the constant-speed response to a square-wave longitudinal cockpit control input shall meet the limits of Figure 4a. Aircraft that fail this requirement and are Level 2 by either 4.2.1.2.1 or 4.2.1.2.2 shall be considered to have Level 3 flying qualities. Parameters required for Figure 4a are defined in Figure 4b. This requirement applies to all aircraft Classes, Flight Phase Categories and Mission Task Elements.*

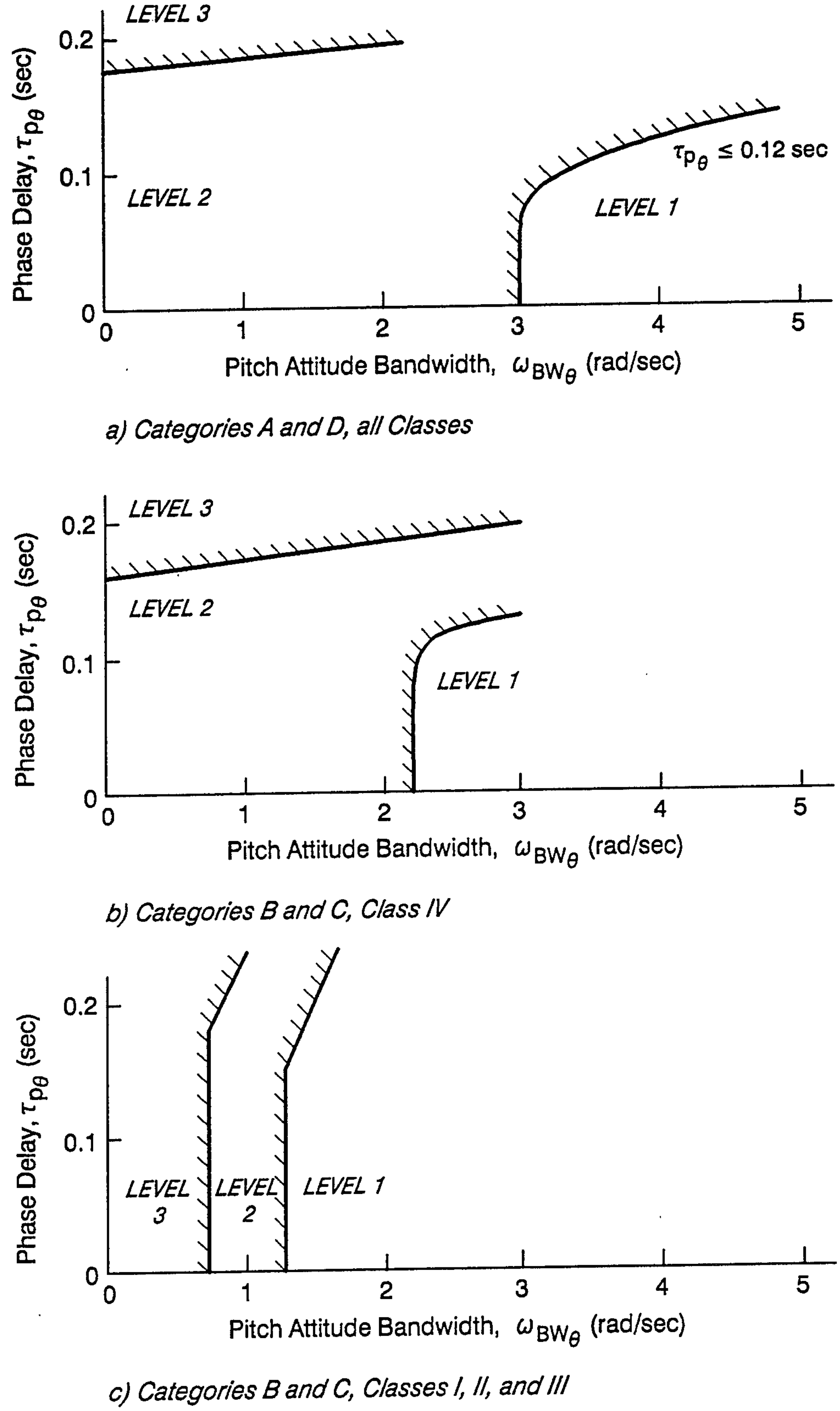


Figure 1(4.2.1.2). Limits on Short-Term, Small-Amplitude Pitch Response to Pitch Controller (Bandwidth)

Phase Delay:

$$\tau_p = \frac{\Delta\Phi 2\omega_{180}}{57.3\,(2\omega_{180})}$$

Note: if phase is nonlinear between ω_{180} and $2\omega_{180}$, τ_p shall be determined from a linear least squares fit to phase curve between ω_{180} and $2\omega_{180}$

Rate Response-Types:

ω_{BW} is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$

Attitude Response-Types:

$\omega_{BW} \equiv \omega_{BW_{phase}}$

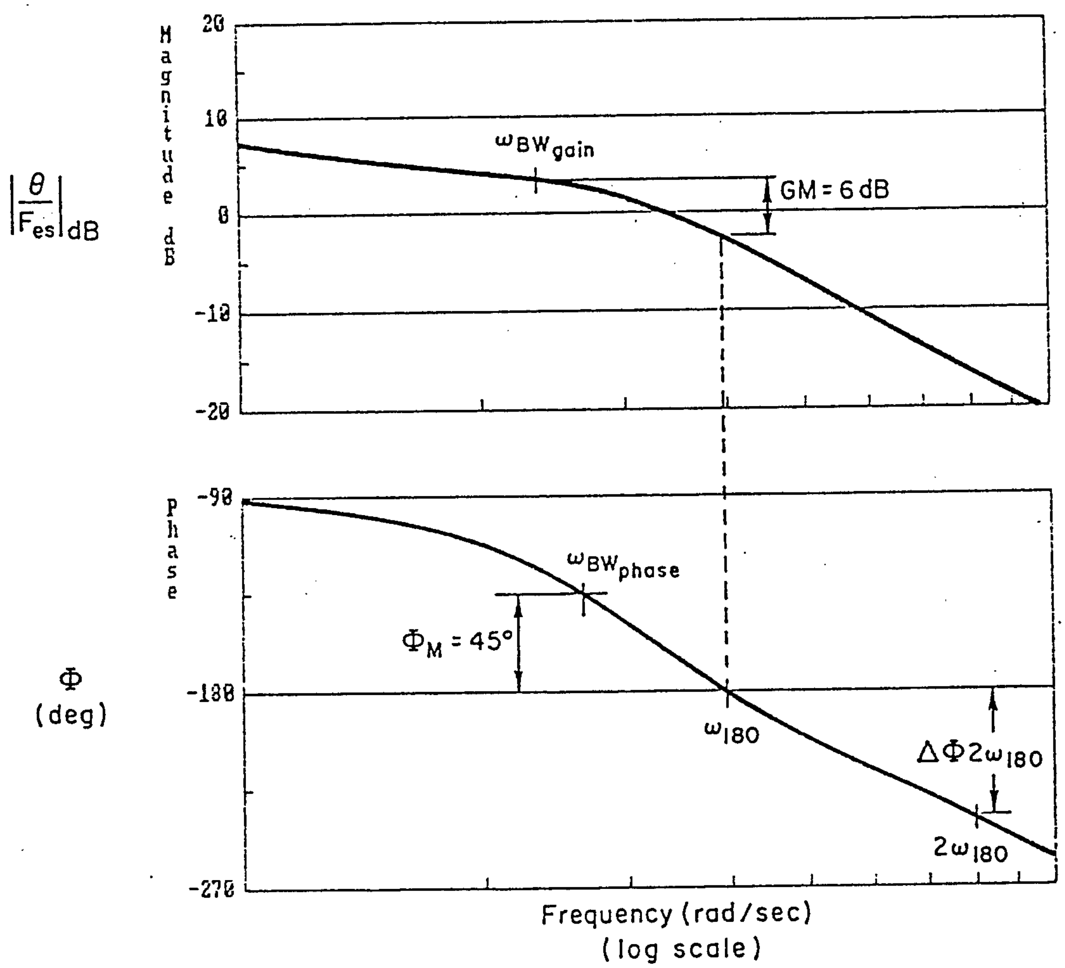


Figure 2(4.2.1.2). Definitions of Bandwidth and Phase Delay

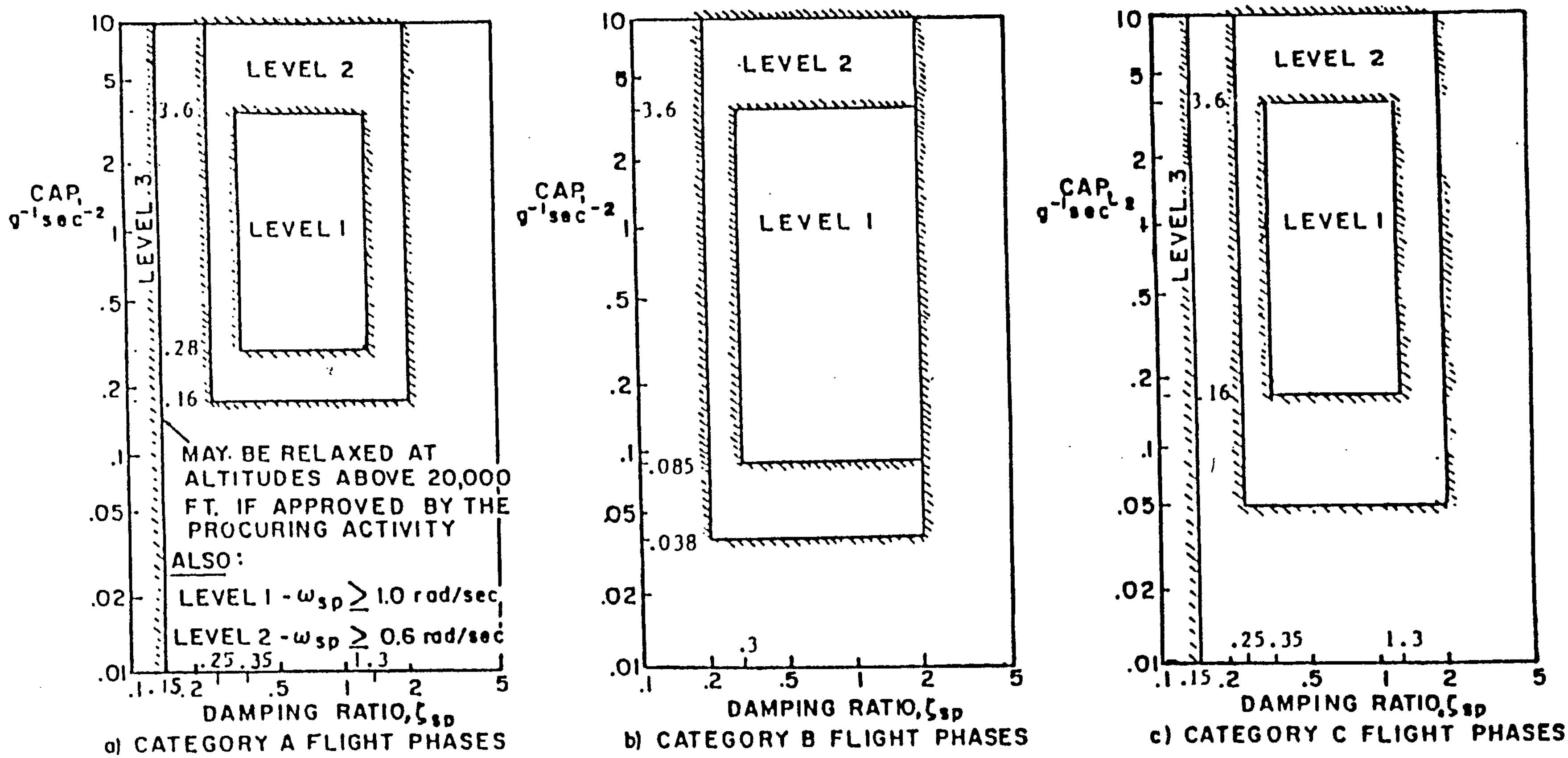


Figure 3 (4.2.1.2). Short-Period Dynamic Requirements for Conventional Response-Types

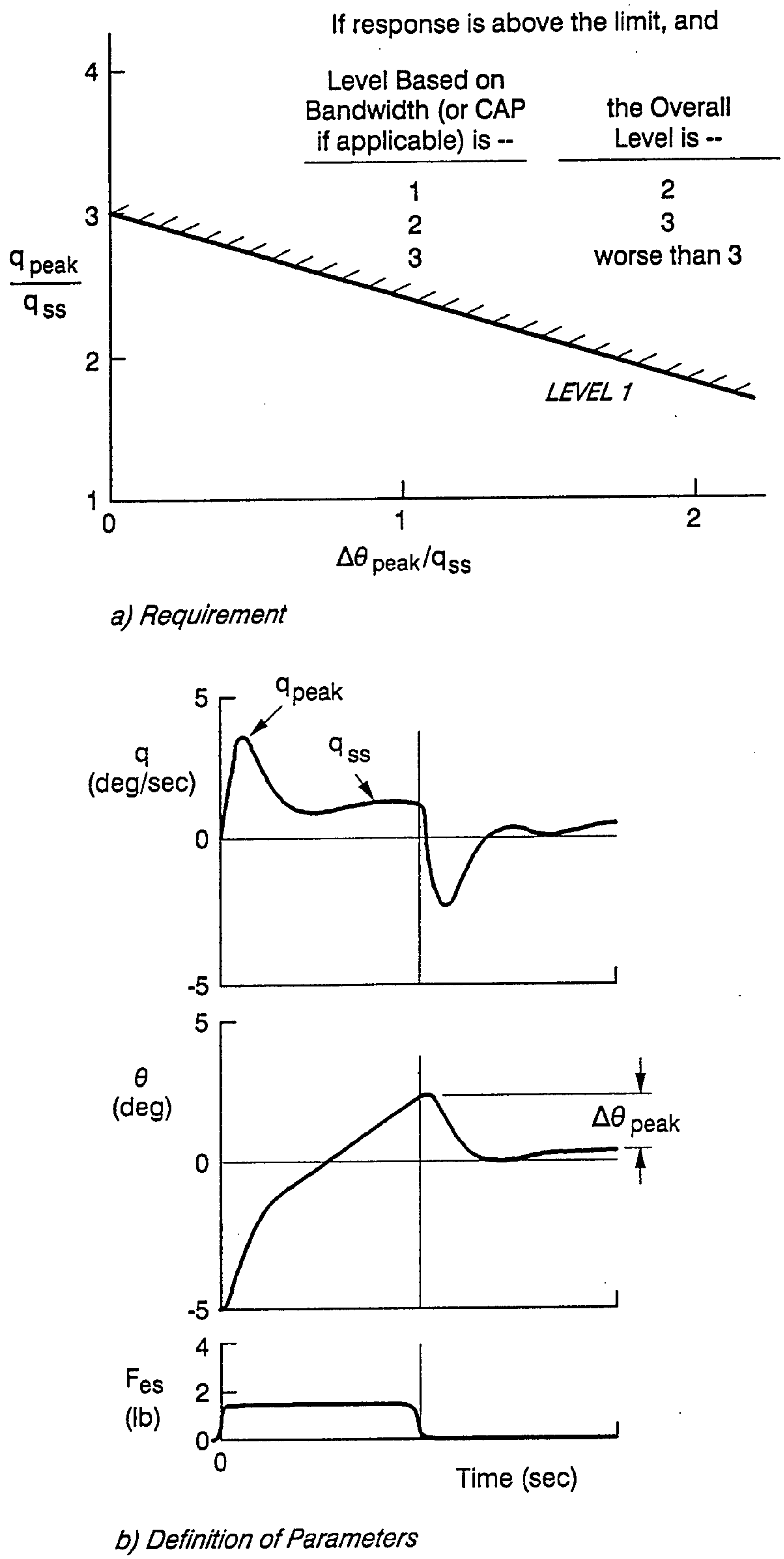


Figure 4(4.2.1.2). Pitch Rate Overshoot and Pitch Attitude Dropback Requirement for Rate and Conventional Response-Types

TABLE 1(4.2.1.2). LIMITS EQUIVALENT TIME DELAY
(Including Feel System)

LEVEL	ALLOWABLE DELAY (sec)	
	CLASS I, II-L, III	CLASS II-C, IV
1	0.18	0.15
2	0.23	0.20
3	0.27	0.25

τ_e is the greater of τ_{e_θ} and τ_{e_n}

2. REQUIREMENT RATIONALE

Pitch control of conventional aircraft is a vital element of flying qualities, both as a primary control axis (for example, in pointing the aircraft during gunnery) and as an indirect way of controlling the aircraft flight path (for example, in glide path control for landing).

3. REQUIREMENT GUIDANCE

In MIL-STD-1797A the "classical" CAP requirement is given as the preferred form for specifying short-term response. Five other criteria are included as alternatives. Unfortunately, there is no guidance to the user on which of the requirements to apply for what situation. Much has been learned about the applications of these criteria in recent years, and it is obvious that there is a serious need to rework the requirements for this paragraph.

Six alternatives are too many, even for a reference document. There must be a clear criterion to be applied for all aircraft procurements. Despite the statement that CAP is the "preferred" form, there is ample evidence that the CAP criteria suffer real disadvantages when the aircraft's response characteristics depart radically from the classical form. The proposed new requirements, based on the pitch attitude Bandwidth criteria from MIL-STD-1797A, have been proven to be insensitive to differences in response type. Because there is a strong allegiance to the "classical" requirements based on CAP, these requirements have been retained as an alternative only in the event that the response type in question is appropriate for their use.

This section of the military standard is clearly the most controversial, and it continues to undergo scrutiny from the flying qualities community. As a result of this attention, a rather lengthy discussion follows. The discussion in this section of the report is limited to a review of the criteria of MIL-STD-1797A and their applicability, including justifications for the proposed Bandwidth and dropback

requirements. Because this discussion alone takes a considerable amount of space, a description of the supporting data for the new requirements has been moved to an appendix (Appendix E).

The requirements of MIL-STD-1797A are not reviewed in detail. It is assumed that the reader is familiar with the philosophies of all of the requirements, and only the differences between them will be covered here.

a. The Requirements of MIL-STD-1797A

Table 2 summarizes the six alternative short-term pitch response criteria in MIL-STD-1797A. A roadmap for the use of the criteria is given in Table 3 as a function of the pitch response type. Because most of the criteria listed were developed for conventional or rate-augmented airplanes, they may be applied for these response types. The criteria based on $\omega_{sp}T_{\theta_2}$, Neal-Smith, and TPR, and the Nichols-chart portion of Gibson's criteria, are considered to be suitable for design guidance only, for the reasons outlined in Table 2. Only the Bandwidth criteria are appropriate for response types dominated by pitch or flight path attitude, as shown by the examples that follow.

b. Example Application of MIL-STD-1797A Criteria

The designations in Table 3 are best illustrated by applying each of the listed criteria to several example response types. For this four different response types will be used. The dynamics for these systems are published in Ref. 27, where pilot ratings are also available from a ground-based simulation. The simulation evaluated several competing response types for the precision landing of an advanced hypersonic transport in varying atmospheric conditions, including gusts and windshears. The four systems are:

- Flight path command/flight path hold (or gamma command/gamma hold, GCGH). This was the best of the systems. Four pilots flew the GCGH system and assigned an average HQR of 2.5.
- Attitude command/attitude hold (ACAH). The average HQR for this system was 2.9, or solidly Level 1.
- Rate command/attitude hold (RCAH) with high pitch rate overshoot. The high overshoot was objectionable to the pilots, so this system was abandoned early in the simulation. The average rating from two evaluations by one pilot was a 4, or Level 2.
- Rate command/attitude hold (RCAH) with low pitch rate overshoot. This system was reasonably well liked, with an average rating from three pilots of 3.67. Hence it was just barely Level 2.

TABLE 2(4.2.1.2).
ALTERNATIVE SHORT-TERM PITCH RESPONSE CRITERIA IN MIL-STD–1797A

1.	CAP or MIL-F-8785C Criteria ("Preferred Form)" – Developed for Conventional "Classical" Airplanes – Difficult or Impossible to Apply for Unusual Modes and attitude Augmentation – Data Bases for Highly-Augmented Aircraft (Neal-Smith, LAHOS) Are in Conflict With the Requirements
2.	$\omega_{sp}T_{\theta_2}$, ζ_{sp} , τ_θ Criteria – Closely Related to CAP, Same Observations Apply
3.	Transient Peak Ratio, Rise Time, Time Delay Criteria – Applicable Only to Speed-Constrained Response for Rate Systems – Specify Pitch Rate Only, Not Flight Path – May Be Incorrect Since Limits Were Based on Mapping CAP (a Flight Path/Attitude Requirement) into Attitude-Only Limits – Time-Domain Criteria Are Highly Subject to Interpretation
4.	Bandwidth, Phase Delay – Specify Attitude Only (Requires an Additional Flight Path Requirement) – In Combination With Dropback, More Effective in Specifying Flying Qualities Than Any Other Criteria – Only Criteria That Are Applicable to All Response-Types
5.	Pilot-in-the-Loop Criteria (Neal-Smith) – Application Requires Extensive Closed-Loop Analysis That is Impossible for a Specification – Applicable to Attitude Response (Not Flight Path) for Rate and Conventional Response-Types Only – Proper Application Specifies Unrealistic Closed-Loop Pilot/Vehicle Operations (Low Closed-Loop Resonance and High Phase Margins) That Are Counter to Actual Piloted Operations (e.g., Ref. 3) – Continued Use as a Criterion Will Require Considerable Refinements
6.	Dropback and Nichols Chart Boundaries – Not Actually "Criteria" – i.e., No Levels, No bases for Comparison, No Data Correlations to Indicate Effectiveness of Methods – Phase-Rate is Closely Related to Phase Delay in Bandwidth – Dropback Has Shown Sufficient Promise to Include it as a Supplement to Bandwidth and CAP for Rate Response-Types

TABLE 3(4.2.1.2).
ROADMAP FOR SHORT-TERM PITCH RESPONSE CRITERIA

RESPONSE-TYPE	SPECIFICATION AND DESIGN CRITERIA	CRITERIA FOR DESIGN GUIDANCE ONLY	CRITERIA NOT APPLICABLE
Conventional	Bandwidth (or CAP) Plus Dropback	$\omega_{sp}T_{\theta_2}$, Neal-Smith Gibson Nichols-Chart Boundaries	TPR
Rate or RCAH	Bandwidth Plus Dropback	CAP $\omega_{sp}T_{\theta_2}$, Neal-Smith Gibson Nichols-Chart Boundaries TPR	None
Attitude-Augmented (including ACAH and GCGH)	Bandwidth	None	Dropback CAP, $\omega_{sp}T_{\theta_2}$, Neal-Smith Gibson Nichols-Chart Boundaries

Bandwidth. — The Bandwidth characteristics of the four systems are included in the data analysis of Appendix E. Both the GCGH and ACAH response types have Level 1 pitch attitude and flight path Bandwidths. The high-overshoot RCAH system is also Level 1, though its overshoot ratio is near the limit. The low-overshoot RCAH system is on the margin between Levels 1 and 2 in both pitch attitude and flight path Bandwidths.

CAP. — Application of the CAP criteria will clearly show that these criteria are not applicable to the GCGH and ACAH response types. First, use of CAP requires the determination of an equivalent systems model of the aircraft. The effective response dynamics of an attitude or flight path command system are very different from those of a conventional airplane, and hence the "classical" (short-period) response form defined in MIL-STD-1797A is not appropriate. Second, although a proper form of equivalent system may be defined, this form differs from that used to generate the CAP boundaries in the first place.

Despite these statements, it is insightful to examine the consequences of attempting to apply equivalent systems to all of the example response types. MIL-STD-1797A specifies that a simultaneous match be used, matching the responses of pitch rate and normal acceleration (the latter measured at the

airplane's center of rotation) to stick force or position over a frequency range of 0.1-10 rad/sec. The full-order and equivalent lower-order transfer functions for q/F_{es} and a_z/F_{es} for all of the systems are listed in Table 4.

When the rules of MIL-STD-1797A are followed for the GCGH system, a very poor match results, with an equivalent value of $1/T_{\theta_2}$ = 0.084 rad/sec, compared to the airplane value of 0.849 rad/sec (Table 4a). The mismatch numbers indicate that the major problem was in the fit to normal acceleration. The resulting equivalent n/α = 0.78 g/rad, reflecting a very poor representation of the actual airplane. The computed value of CAP, based on this n/α, is 2.9, and the equivalent short-term damping ratio is 0.28.

There are two ways to compare this match for the GCGH system with the CAP requirements. Since the equivalent-system-derived value of CAP is 2.9, this value may be used. Alternatively, it may be assumed that the correct value of CAP to apply to the requirements is that resulting from the airplane's actual response, corresponding to the airplane's value of $1/T_{\theta_2}$. The resulting points are shown for both methods on the MIL-STD-1797A requirements in Figure 5a. Because of the low equivalent damping, both points are outside the Level 1 limits. With the additional high equivalent time delay of 0.145 sec, the equivalent systems suggest possibly Level 2 or 3 handling qualities.

The problem of non-real $1/T_{\theta_2}$, and therefore n/α, can be avoided by matching pitch rate alone with $1/T_{\theta_2}$ fixed at the value specified by the airplane's actual n/α. The results of the equivalent-systems match with this transfer-function form are also given in Table 4a and plotted on Figure 5a. The equivalent damping is even lower, at 0.22, resulting in predicted Level 3 flying qualities. The mismatch value is also higher, reflecting a very poor fit.

If $1/T_{\theta_2}$ were allowed to be totally free in the fitting process, with only q/F_{es} used in the match, mismatch is small; damping ratio is now Level 1 but CAP is well above the Level 1 limit and time delay is higher (Figure 5a and Table 4a).

A final possible approach to CAP might be to perform an equivalent-systems match to the primary response variable: flight path angle, γ. The resulting model is obtained with a high mismatch. As Table 4a and Figure 5a show, using this LOES fit and the airplane's actual n/α results in equivalent dynamics in the Level 1 region of CAP, but with an equivalent time delay of 0.262 sec, or worse than Level 3. This shows that, even if it were assumed that CAP relates to the LOES model for flight path, the predicted flying qualities are still very poor.

TABLE 4(4.2.1.2). EQUIVALENT SYSTEM APPLICATIONS TO EXAMPLE SYSTEMS

a) Flight Path Command/Flight Path Hold (HQRs: 1.5, 3, 3, 3, 2.5, 2)

Model Form	$1/T_{\theta_2}$	q/F_{es}	a_z/F_{es} (at c.r.)	Mismatch
High Order System	N/A	$\frac{8.74(0)(0.00521)(0.849)(1.2)[-0.866,139]}{(-0.021)(0.065)(2.47)(3.75)[0.526,1.24][0.896,134]}$	$\frac{-2149(0.00371)(-0.0199)(1.2)[-0.866,139]}{(-0.021)(0.065)(2.47)(3.75)[0.526,1.24][0.896,134]}$	N/A
Simultaneous Match of q & a_z (per MIL-STD-1797A)	Free	$\frac{1.53(0.084)e^{-0.145s}}{[0.28,1.50]}$	$\frac{-213e^{-0.104s}}{[0.28,1.50]}$	183 (q); 957 (a_z)
Match q Alone	Fixed	$\frac{0.985(0.849)e^{-0.112s}}{[0.22,1.72]}$	N/A	758
Match q Alone	Free	$\frac{1.37(0.031)e^{-0.144s}}{[0.45,1.21]}$	N/A	35
Match γ/F_{es}*	N/A	$\frac{0.25e^{-0.391s}}{[0.54,0.96]}$	N/A	266

*LOES for γ/F_{es} transfer function of the form $Ke^{-\tau s}/[\zeta,\omega_n]$; high order system is

$$\frac{-0.31(-0.022)(1.2)(-1.98)(3.05)[-0.866,139]}{(-0.021)(0.665)(2.47)(3.75)[0.526,1.24][0.896,134]}$$

b) Attitude Command/Attitude Hold (HQRs: 3, 3, 4, 2, 3, 2.5)

Model Form	$1/T_{\theta_2}$	q/F_{es}	a_z/F_{es} (at c.r.)	Mismatch
High Order System	N/A	$\frac{9.39(0)(0.00521)(0.849)(2)[-0.866,139]}{(0.00525)(0.554)(2.11)(3.75)[0.47,1.97][0.898,134]}$	$\frac{-2150(0.00371)(-0.0199)(2)[-0.866,139]}{(0.00525)(0.554)(2.11)(3.75)[0.47,1.97][0.898,134]}$	N/A
Simultaneous Match of q & a_z (per MIL-STD-1797A)	Free	$\frac{1.95(0.074)e^{-0.158s}}{[0.27,1.78]}$	$\frac{-250e^{-0.116s}}{[0.27,1.78]}$	243 (q); 964 (a_z)
Match q Alone	Fixed	$\frac{1.21(0.849)e^{-0.123s}}{[0.19,2.00]}$	N/A	761
Match q Alone	Free	$\frac{1.76(0.015)e^{-0.160s}}{[0.49,1.49]}$	N/A	92
Match θ/F_{es}*	N/A	$\frac{1.76e^{-0.162s}}{[0.50,1.44]}$	N/A	94

*LOES for transfer function of the form $Ke^{-\tau s}/[\zeta,\omega_n]$

TABLE 4(4.2.1.2). (CONCLUDED)

c) Rate Command/Attitude Hold With High Pitch Rate Overshoot (HQRs: 2, 6)

Model Form	$1/T_{\theta 2}$	q/F_{es}	a_z/F_{es} (at c.r.)	Mismatch
High Order System	N/A	$\frac{18.8(0.00521)(0.5)(0.849)(2)[-0.866,139]}{(0.00525)(0.554)(2.11)(3.75)[0.47,1.97][0.898,134]}$	$\frac{-4300(0.00371)(-0.0199)(0.5)(2)[-0.866,139]}{(0)(.00525)(0.554)(2.11)(3.75)[0.47,1.97][0.898,134]}$	N/A
Simultaneous Match of q & a_z (per MIL-STD-1797A)	Free	$\frac{2.97(1.01)e^{-0.145s}}{[0.35,1.72]}$	$\frac{-743e^{-0.150s}}{[0.35,1.72]}$	41 (q); 57 (a_z)
Match q Alone	Fixed	$\frac{3.17(0.849)e^{-0.150s}}{[0.37,1.68]}$	N/A	48
Match q Alone	Free	$\frac{2.74(1.47)e^{-0.137s}}{[0.30,1.93]}$	N/A	32

d) Rate Command/Attitude Hold With Low Pitch Rate Overshoot (HQRs: 3, 3, 5)

Model Form	$1/T_{\theta 2}$	q/F_{es}	a_z/F_{es} (at c.r.)	Mismatch
High Order System	N/A	$\frac{9.39(0)(0.00521)(0.849)(2)[-0.866,139]}{(0)(-0.0023)(2.19)(3.75)[0.74,1.44][0.895,134]}$	$\frac{-2150(0.00371)(-0.0199)(2)[-0.866,139]}{(0)(-0.0023)(2.19)(3.75)[0.74,1.44][0.895,134]}$	N/A
Simultaneous Match of q & a_z (per MIL-STD-1797A)	Free	$\frac{1.47(0.98)e^{-0.145s}}{[0.56,1.22]}$	$\frac{-363e^{-0.149s}}{[0.56,1.22]}$	43 (q); 50 (a_z)
Match q Alone	Fixed	$\frac{1.54(0.849)e^{-0.149s}}{[0.58,1.18]}$	N/A	48
Match q Alone	Free	$\frac{0.99(4.88)e^{-0.107s}}{[0.55,2.11]}$	N/A	12

Notes: 1) Matches performed over the range 0.1 - 10 rad/sec
2) Transfer functions listed with "shorthand" notation: $(a) = (s + a)$, $[\zeta, \omega] = [s^2 + 2\zeta\omega s + \omega^2]$
3) Complete model description published in Ref. 2
4) $1/T_{\theta 2} = 0.849$ rad/sec; $V_T = 300$ ft/sec; $n/\alpha = 7.9$ g/rad

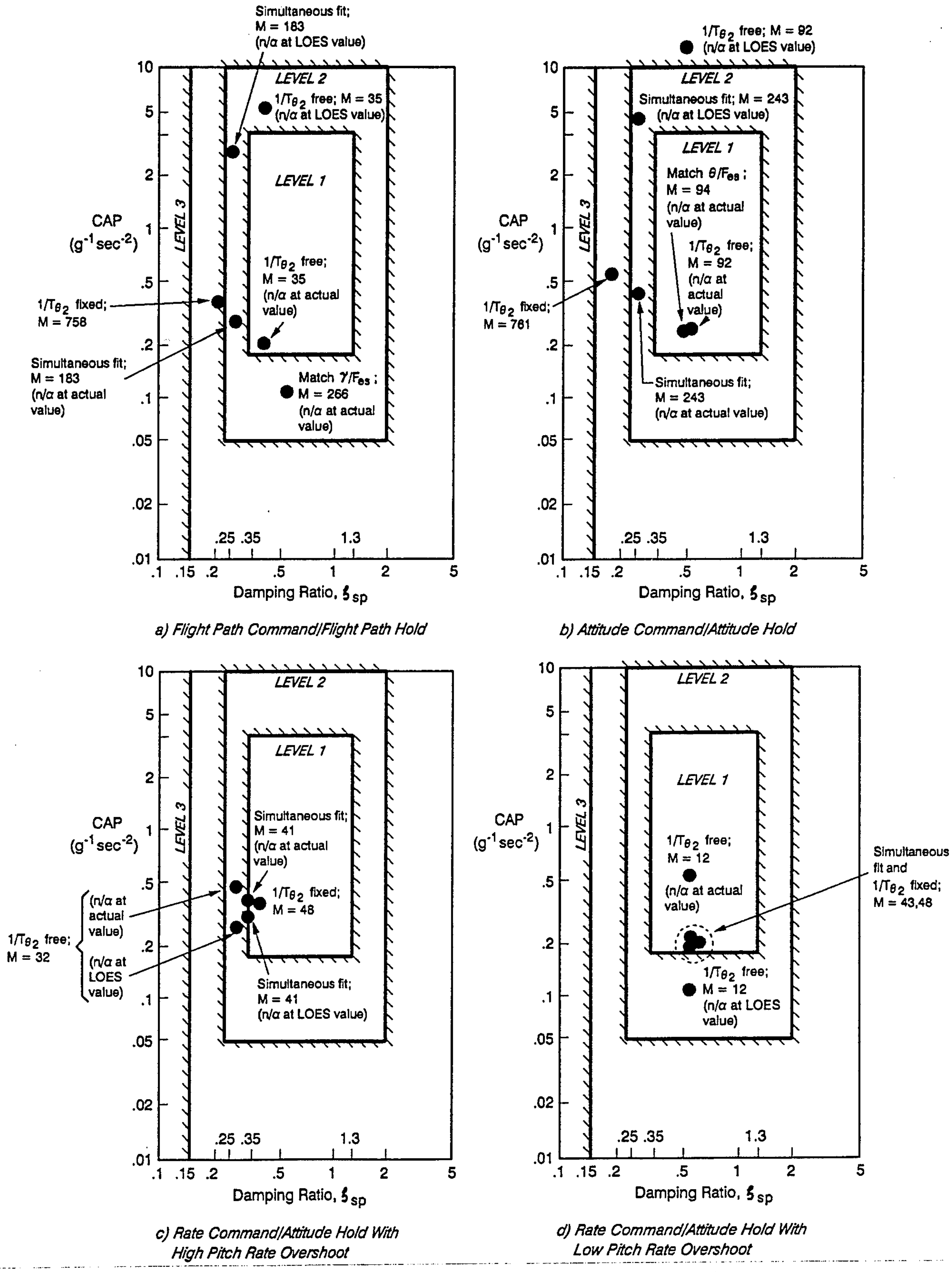


Figure 5(4.2.1.2). Equivalent-System Applications for Example System
(MIL-STD-1797A Category C Requirement)

A similar approach may be taken with the ACAH system, resulting in the dynamics listed in Table 4b and plotted in Figure 5b. The only methods that obtain close to a Level 1 response are if $1/T_{\theta_2}$ is freed or ignored completely — neither of which is regarded as the "correct" way to perform the fit. In addition, of course, it may be more coincidence than correlation that places the equivalent dynamics of the ACAH system in the Level 1 region of Figure 5b.

For both of the RCAH response types (Tables 4c and 4d), the answers are similar with $1/T_{\theta_2}$ fixed and freed, especially for the high-overshoot case (Figure 5c). With $1/T_{\theta_2}$ free the fits for the low-overshoot case (Figure 5d) are somewhat different from those obtained from $1/T_{\theta_2}$ fixed or with a simultaneous match. The answers are also consistent with pilot comments and ratings: the high-overshoot case (Figure 5c) was Level 2 because of excessive pitch rate overshoot, manifested here as a low equivalent damping ratio; the low-overshoot case (Figure 5d) was Level 2 because of sluggish pitch response.

As mentioned above, there is no physical meaning to the "$1/T_{\theta_2}$ free" LOES matches for any of the systems. On the other hand, it may be possible to determine the appropriateness of the equivalent-systems concept based on performing matches both ways. If the answers differ considerably, it is probably not correct to use CAP criteria, and other criteria, such as Bandwidth, must be applied.

As these examples have demonstrated, there is no fitting method that will give both a reasonable answer (in terms of an equivalent model) and the correct answer (in terms of Level of flying qualities) for the application of CAP to flight path command systems, and possibly to attitude command systems.

$\omega_{sp}T_{\theta_2}$ Criteria. — These criteria are modifications to CAP and require the same use of equivalent systems. Therefore, the shortcomings discussed above apply here as well.

TPR. — Chalk's transient peak ratio and rise time criteria are time-domain-based and include parameters measured from steady-state pitch rate for a step input. By definition, the steady-state pitch rate for a flight path or attitude command system is zero or near zero, so if these criteria were applied they would predict extremely poor flying qualities. The criteria were developed for rate-command response types, where there is a clearly measurable steady-state rate. They do not apply to attitude response types.

Both of the rate response types fail some portion of these criteria. For example, the equivalent time delay as defined for these criteria is approximately 0.3 sec for both cases, but the Level 3 maximum limit is 0.21 sec — therefore both systems should be worse than Level 3 by this requirement. The transient peak ratio for the high-overshoot system is 0.7, making it Level 3 (the Level 2 limit is 0.60). The low-overshoot system meets the TPR requirement. Both systems are Level 1 in terms of rise time. So overall,

the flight path and attitude command systems are not applicable, and the rate command systems are Level 3 (or worse) by the criteria, in contrast to the Level 2 (almost Level 1) pilot ratings.

Pilot-in-the-Loop [Neal-Smith] Criteria. — The Neal-Smith criteria are quite similar in concept to Bandwidth. They involve determination of the closed-loop system that results from effective pilot compensation in controlling pitch attitude, assuming a target frequency for pilot control. Unfortunately, because they involve closed-loop analysis, the Neal-Smith criteria are not amenable to use in a specification. In a way, the Neal-Smith analysis suffers from shortcomings similar to those for equivalent-system analysis approaches: the answer obtained may be sensitive to the analysis method and selection of the pilot model parameters.

Using the pilot model rules of MIL-STD-1797A attempts were made to generate a closed-loop pilot-vehicle system for all of the response types at a bandwidth of 2.5 rad/sec, as required by MIL-STD-1797A. It was not possible to obtain Level 1 response dynamics (closed-loop droop no more than -3 dB and resonance no greater than 3 dB) for the attitude or flight path command systems with any of the pilot model forms allowed. Attempts to minimize droop resulted in closed-loop resonance and vice versa.]

The principles behind the Neal-Smith criteria, assuming piloted closed-loop control of attitude, are certainly valid for all response types. The basic advantage to attitude command, however, is that the pilot is not required to provide continuous closed-loop control of attitude since the SAS performs this function. Then the pilot only has to apply intermittent control. This is counter to the basic theory of the Neal-Smith analysis method, which assumes that the pilot will provide full-time attitude control. Further work is required to determine the required adjustments to the bandwidths, pilot model forms, or required closed-loop responses for flight path or attitude response types.

It is also possible that the current bandwidths are too high, as discussed in the analysis presented in Ref. 25. The form of the Neal-Smith criteria adopted in MIL-STD-1797A lacks some of the critical insights provided by this analysis approach — specifically, the sensitivity of the closed-loop response to variations in target bandwidth and the importance of both closed-loop resonance and pilot compensation on pilot opinion. The Neal-Smith criteria as originally developed may be effective PIO prediction tools as well.

Dropback. — Dropback is not applicable to the flight path or attitude systems. It is a measure of pitch rate overshoot, and these systems have essentially zero steady-state pitch rate in response to a step control input. Dropback is a valuable auxiliary flying qualities criterion, as is clearly demonstrated in Appendix E, for rate response types. Both of the rate systems pass the requirement.

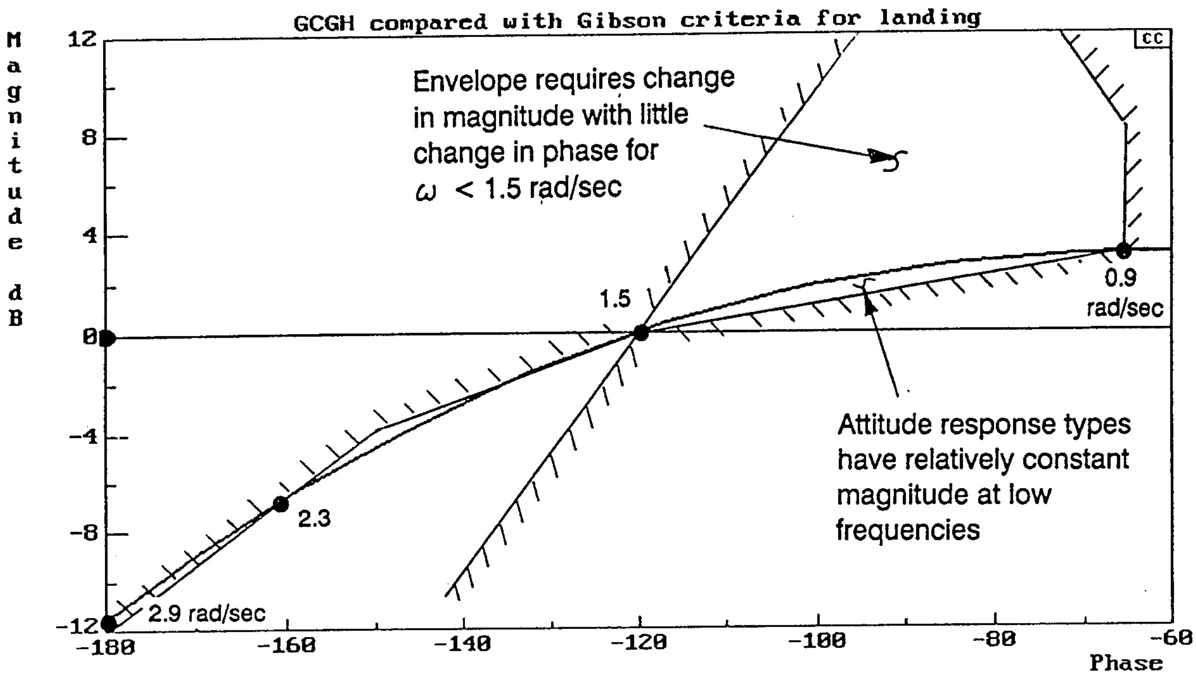
Gibson's Nichols-chart boundaries. — The greatest single shortcoming with the Gibson frequency-domain criteria, as indicated in Table 2, is that they do not specify Levels. In addition, they assume a conventional-looking response form. As evidence of this, Figure 6 shows the Gibson landing limits on a Nichols chart of θ/F_{es} for the GCGH example. The envelope defined by Gibson requires a region of changing magnitude with relatively constant phase angle for frequencies well below 1.5 rad/sec (upper right portion of Figure 6a). For example, a system with k/s-like dynamics (magnitude slope of -20 dB/decade with phase angle of -90 deg) easily passes the low-frequency portion of the Gibson criteria. By definition, however, attitude response types have relatively flat magnitude curves at low frequencies, as the Bode plot of Figure 6b demonstrates. The example GCGH system violates the Gibson limits for all frequencies below 0.9 rad/sec. Hence the limits as drawn are not applicable to this type of system.

c. Selection of the Proposed Limits

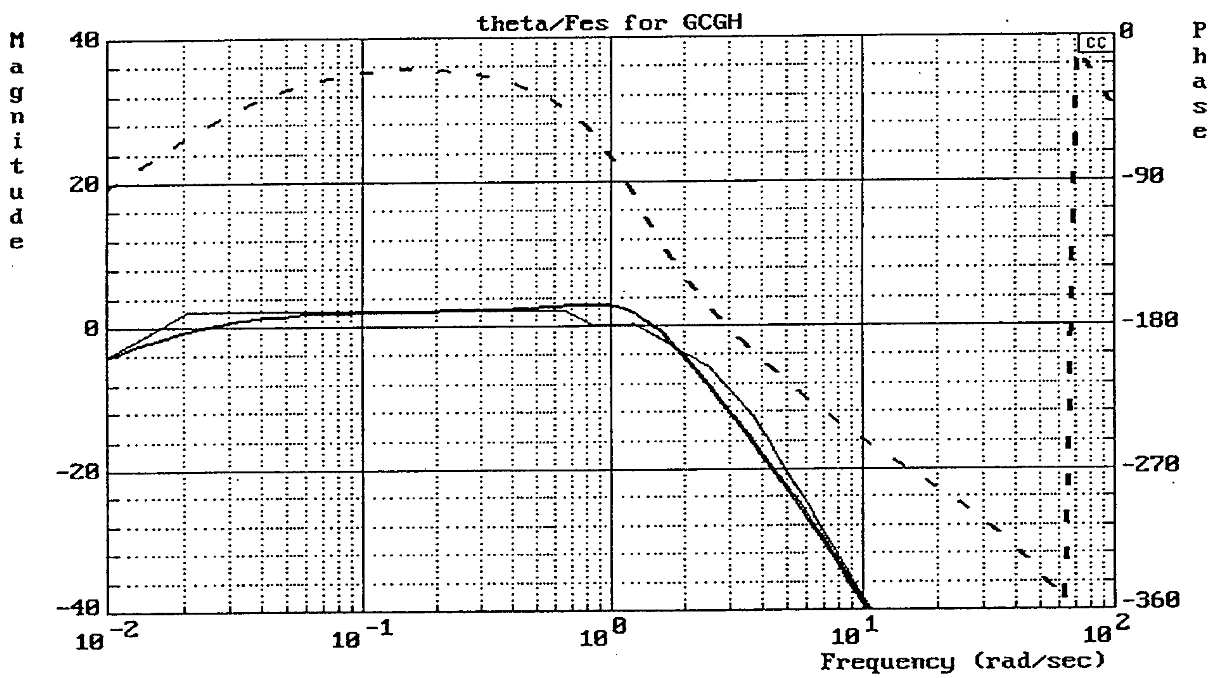
The current usable data base for defining short-term response requirements is relatively limited (Appendix E). The data are, in general, limited to fighter-type (Class IV) and transport-type (Class III) airplanes performing only a few tasks: HUD or target tracking (Flight Phase Category A), precision offset landing (Flight Phase Category C), etc. For these airplane Classes and Mission Task Elements it is possible to generate well-defined requirements. Unfortunately, there are many other Mission Task Elements under each of the Flight Phase Categories for which no information at all is available. In addition, of course, there are two other Categories (B and D) and two other Classes of airplanes (I and III) that are not addressed at all.

This shortage of information means that some assumptions must be made. These assumptions were made the first time the modern classifications of aircraft and flight phases were adopted, in MIL-F-8785, so there is nothing new. For the Bandwidth requirements of Figure 1 the following logic was used in grouping the various Flight Phase Categories and airplane Classes:

- Tasks in Flight Phase Category A, Aggressive and Precision Tasks (primarily tracking a maneuvering target, either another airplane or on a HUD or head-down display), may be considered natural extensions of similar tasks in Category D, Aggressive and Non-Precision Tasks (gross acquisition using loaded roll). In other words, accomplishment of a Category A task implies a requirement to perform a Category D task first. Therefore it seems reasonable to apply the same Bandwidth requirements to both Categories. This assumption is valid, of course, only as long as no nonlinearities are encountered in performing Mission Task Elements in either Category. A very logical distinction between Categories A and D is in the requirements for control power, and the likelihood of reaching airplane physical limits when performing the (generally) large-amplitude Category D tasks.



a) Criterion Boundaries for Landing on Nichols Chart of θ/F_{es}



b) Bode Plot of θ/F_{es}

Figure 6(4.2.1.2). Comparison of Example Flight Path Command System with Gibson Nichols-Chart Criteria

- The same reasoning does not necessarily hold for Category C, Precision and Non-Aggressive Tasks (for example, precision landing) and Category B, Non-Precision and Non-Aggressive Tasks (for example, non-precision landing). The intent of the separation in these categories is, in fact, to recognize that a comparable level of response is not required for both. In the specific case of landing, however, it would seem reasonable to assure that all airplanes possess a similar level of response, even if some are not designed to routinely perform precision landings. The built-in margin of safety for these airplanes will help protect against the possibility of a catastrophe if there is ever a need to perform a precision landing. In other words, the application of the Category C limits to Category B is a concession to the "worst-case" possibility.

- Bandwidth requirements for Categories A and D are to be applied to any airplane expected to perform the tasks, regardless of airplane Class. This is in keeping with the mission orientation of the military standard: the response demands placed on an airplane should be based on what is required of that airplane, not on its size. Since most tasks in Categories A and D will be flown only by fighters and highly maneuverable trainers, this designation is appropriate. If, however, a small transport were expected to perform maneuvers such as low-level ground attack, it should have a good pitch attitude Bandwidth, or it is likely to exhibit degraded flying qualities.

- Almost all of the supporting data for Class IV (highly maneuverable, fighter-type) airplanes comes from the USAF variable-stability NT-33A. There are no data for Class I or II airplanes.* For the Bandwidth requirements for Flight Phase Categories B and C, only Class IV airplanes have a separate set of limits, while Classes I and II have been grouped with Class III. Since most light trainers are likely to be unaugmented and hence avoid the handling qualities problems associated with digital computers, filtering, etc., they will probably find it possible to meet the requirements for Class IV airplanes. Until future flight testing shows that the higher Bandwidths are needed, however, it is recommended that the Class III requirements be applied. Remember, again, that if any Class I, II, or III airplane is intended to perform the stringent Category C mission tasks normally connected with fighters, the fighter limits should be applied: base the requirements on mission, not size.

The requirement on pitch rate overshoot versus pitch attitude dropback in Figure 4 is derived from Gibson's concept of dropback (e.g., Ref. 29), but the details of its measurement are slightly different. It is not meant as a "stand-alone" requirement: meeting the Level 1 limit as drawn does not guarantee Level 1 flying qualities. It is an auxiliary requirement to Bandwidth (or CAP), so both the Bandwidth and the overshoot must be Level 1 to assure Level 1 flying qualities. If the airplane's response dynamics are

*This discussion is presented in full recognition of the existence of a very large data base for all Classes of airplanes (such as that analyzed in detail in the background document for MIL-F-8785B, Ref. 28). Most of these data, however, were generated before the advent of the Cooper-Harper scale and often without the imposition of tight performance constraints, as is the norm today. The resulting data base is sometimes in conflict and is generally regarded as inappropriate for defining new requirements. This is not to suggest that such data are necessarily entirely invalid, but that their use requires extensive discussion with little real added benefit to the analysis presented in this report.

Level 1 by the requirements on Bandwidth (or CAP, if appropriate), failing the Figure 4 limit means the overall short-term, small-amplitude response is Level 2. Failure of an otherwise Level 2 airplane to meet the Figure 4 limit indicates Level 3 flying qualities.

As the data analyses of Appendix E clearly demonstrate, the overshoot/dropback limit of Figure 4 applies to all aircraft Classes and Flight Phases.

4. SUPPORTING DATA

The supporting data for the new Bandwidth and Phase Delay requirements are given in Appendix E.

The time delay limits in Table 1 are modified from those in MIL-STD-1797A, and the table introduces the concept of separate limits based on airplane Class. There is considerable evidence that the time delay requirements in the military standard are too stringent for transports (e.g., Ref. 30). Table 5, taken from Ref. 30, lists some examples of time delay limits from various sources. Every research result listed indicates limits greater than those in MIL-STD-1797A. What has not been as clear is 1) whether the limits for fighters are reasonable, and 2) what the limits for transports should actually be.

TABLE 5(4.2.1.2). EXAMPLE OF TIME DELAY REQUIREMENTS
(Reference Numbers are from Ref. 30)

SOURCE	MIL-F-8785C	CALSPAN SUPERSONIC CRUISE RESEARCH		CALSPAN TIFS	DOUGLAS RESEARCH		LOCKHEED RESEARCH		NASA LANGLEY	
REF NO.	4	7		8	—	—	9		10	
DATE	1980/ 1982	1980		1981	1986	1989	1983		1985	
TYPE OF TEST	FLIGHT			MOTION-BASE SIMULATOR						
AXIS	ALL	LONG.	LAT/DIR	ALL	LONG.	LAT	LONG.	LAT	PITCH	ROLL
FQ LEVEL	ALLOWABLE TIME DELAY AT FQ LEVEL BOUNDARY (SEC)									
1	0.10	0.12	0.17	0.20	0.44	0.33	1.10	0.40	0.5	0.3
2	0.20	0.17	0.24	0.27	0.63	0.73	1.60	0.60	1.0	0.7
3	0.25	0.21	0.28	0.43	0.76*	1.10*	2.20	0.70	1.3	0.9
CLASS	FIGHTER			TRANSPORT						

*EXTRAPOLATED

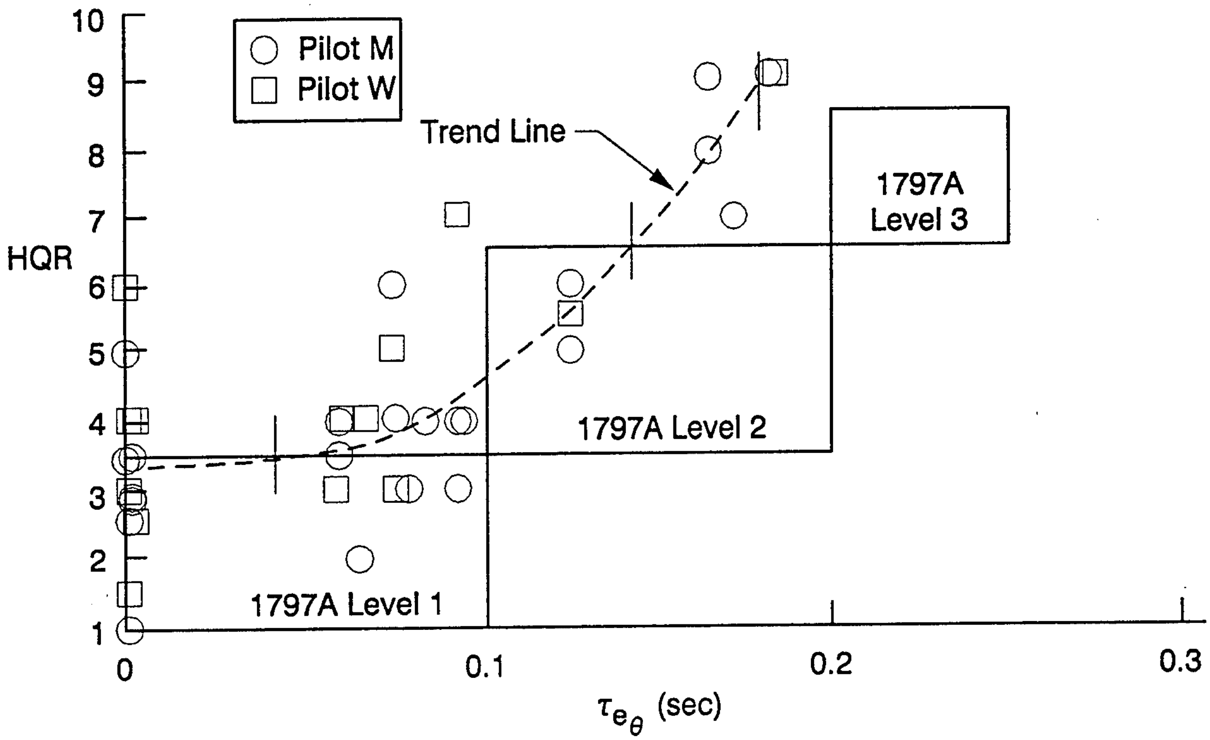
Time delay limits for fighters. – When the draft military standard and handbook (Ref. 10) were written, it was recognized that the time delay limits of MIL-F-8785C were reasonably well-supported by equivalent-system-derived numbers from the Neal-Smith (Ref. 31) and LAHOS (Ref. 32) experiments. These data deserve reanalysis, however, in light of recent revelations of the importance of such phenomena

as Dropback on pilot opinion. Since equivalent delay, short-period response, and Dropback are all interrelated for these data it is difficult to separate out the effects of time delay alone.

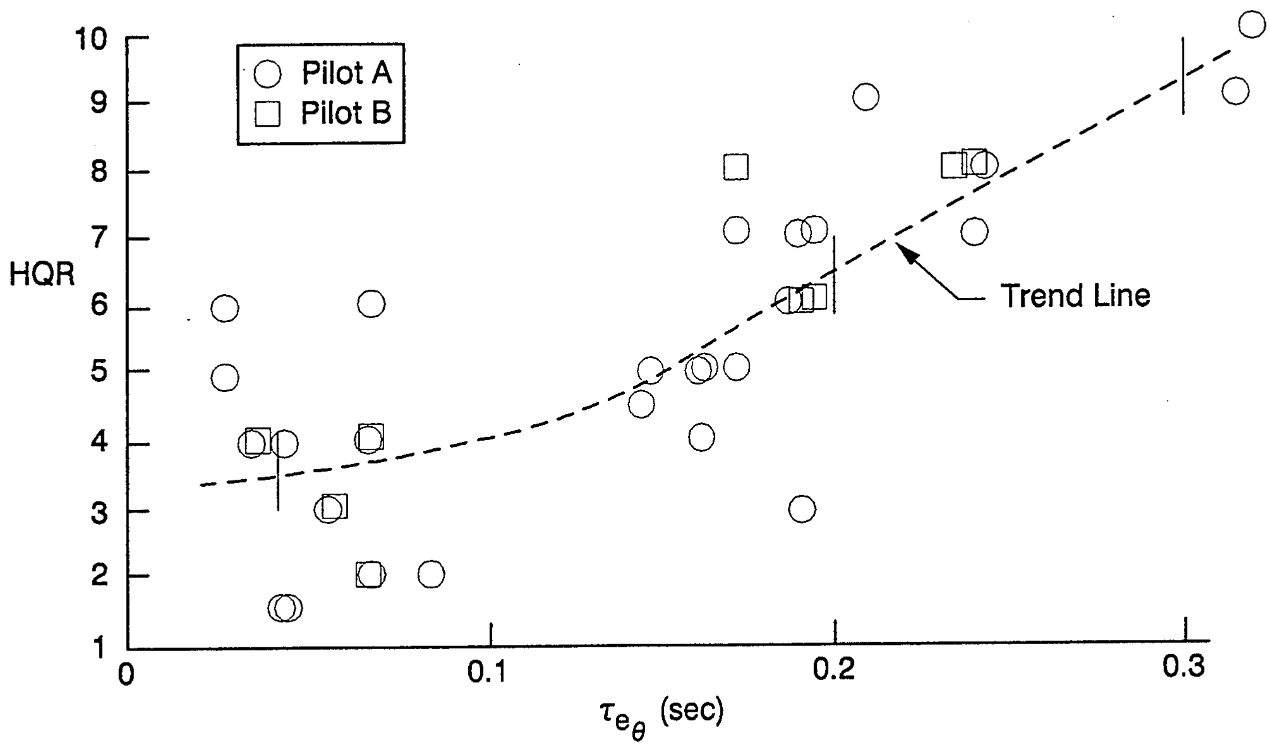
A limited reanalysis was performed as a part of this contract. In an attempt to isolate the effects of time delay alone, only those cases with Level 1 values of equivalent short-period frequency and damping ratio, and acceptable Dropback, *and* for which the pilot-selected value of control sensitivity resulted in a Level 1 stick force per g, were used. Hopefully, the only remaining variable affecting pilot opinion is equivalent time delay. For this analysis the 51 basic force-command configurations from the Neal-Smith experiment were considered (see Appendix E), because equivalent-system models for these cases were readily available.

Based on this process, we are left with 18 cases from the Neal-Smith data base. These are 1B, 1C; 2D, 2E, 2F, 2G, 2H; 3C, 3D; 4D; 5D; 6A, 6B; 7C, 7E, 7F; 8C, and 8D. Individual HQRs for these cases from the two pilots are plotted against equivalent time delay in Figure 7a. (Note that these data do not include the feel system.) There is indeed a very steep trend to the data, as has been observed before. Based on an eyeball trend line, it would seem that the MIL-STD-1797A time delay limits are too lenient, especially for Levels 2 and 3. Unfortunately, it is not clear why so many of the cases with no equivalent time delay at all are Level 2, resulting in an average rating at zero delay of around 3.5. Hence the best cases are only marginally Level 1 at best. If we use the Neal-Smith data to set time delay limits, we might select a Level 1 limit of between 0.07 and 0.10 sec, with Level 2 and 3 limits at about 0.14 and 0.18 sec, respectively — all more stringent than the MIL-STD-1797A limits. If the trend line were arbitrarily lowered to start from an HQR of around 2 (recognizing that there is absolutely no justification to make such an adjustment), the Level 1 limit would be around 0.11 sec and Level 2 around 0.17 sec.

A similar weeding-out process for the LAHOS data results in a total of 27 useful cases. In this case it is easier to list those configurations *not* included. Those excluded were: 1-3, 1-4, 1-11; 2-A, 2-9, 2-10; all 3- cases; 5-1, 5-3, 5-4, 5-5, 5-6, 5-7; and all 7- cases. (The pitch attitude and flight path Bandwidth requirements presented in this report correctly predict the Levels of 24 of these 27 cases.) Figure 7b shows the individual HQRs from the two pilots plotted against equivalent time delay. (Note that these data include the feel system.) There is again considerable data scatter, especially at the low values of time delay. A very rough trend line has been sketched, suggesting a more gradual degradation in HQR with time delay. Given the data scatter it is difficult to say where a Level 1 limit might be; a Level 2 limit is somewhere around 0.2 sec and Level 3 between 0.25 and 0.3 sec, both numbers in general agreement with the MIL-STD-1797A requirements. Recall, however, that these values are with the feel system included, whereas the military standard states that it should be excluded when evaluating time delay.



a) Category A (Neal-Smith Data -- Excludes Feel System)



b) Category C -- Precision Offset Landing (LAHOS Data -- Includes Feel System)

Figure 7(4.2.1.2). Pilot Ratings for Configurations with Level 1 Values of Equivalent Short-Period Frequency and Damping Ratio, and with Level 1 Fs/n and Acceptable Dropback

Interestingly, if the effects of the feel system (which contributed about 0.06 sec of time delay) are removed, the data are quite close to those for the Neal-Smith experiment in Figure 7a.

On the basis of these data, and including the effects of the feel system (which for both experiments added about 0.06 sec of time delay), the time delay limits of Table 1 are recommended for Class IV aircraft. They have been extended to carrier-based Class II airplanes on the hypothesis that the carrier landing task is sufficiently stringent to require these time delay limits no matter what the aircraft Class.

Time delay limits for transports. — A similar analytical approach can be taken by using the TIFS data of Refs. 33 and 34. Because "official" equivalent-systems models for the configurations in these experiments have not been published, this approach was not done for this effort. The limits in Table 1 for Class III airplanes are based on three observations. 1) The effective-time-delay limits of Chalk's TPR serve as a good basic measure of delay for transports. This uses a time-domain definition of time delay, but the effective time delay t_1 is close in value to equivalent-system delay, as long as the major contributor to the delay is *pure* delay (as opposed to lags). These numbers are to be applied without including the effects of the cockpit control feel system. 2) Reference 35 reviewed the effective time delay requirements for transports using a variety of data sources. While this reference recommends a Level 1 limit on t_1, with the feel system included, of 0.13 sec, the most reliable data set, from the Ref. 34 TIFS experiment, suggests a more relaxed limit. These data are shown in Figure 8; they are for only one portion of the total experiment. In this case the only variation is the addition of incremental pure time delay. These few pilot rating points suggest a Level 1 limit around 0.17-0.18 sec and a Level 2 limit of about 0.3 sec. The latter seems too lenient, however, when compared with Chalk's recommended limits. 3) Typical cockpit control feel systems contribute on the order of 0.06 sec of equivalent time delay. For Level 1 this is in excellent agreement with the differences between Chalk's recommended t_1 limit of 0.12 sec (no feel system) and the limit of about 0.18 sec suggested by Figure 8 (feel system included).

In the absence of any real data, it is assumed that the transport time delay limits can also be applied to Class I and II-L airplanes.

In MIL-STD-1797A the limits on equivalent time delay are the same for both pitch and roll. It is important to note that the time delay limits listed in Table 1 are very different from those recommended for roll (see 4.5.1.5). There is no inherent reason that they must be the same; the roll Bandwidth requirements of 4.5.1.1 are quite unlike those for pitch presented in this paragraph (Figure 1).

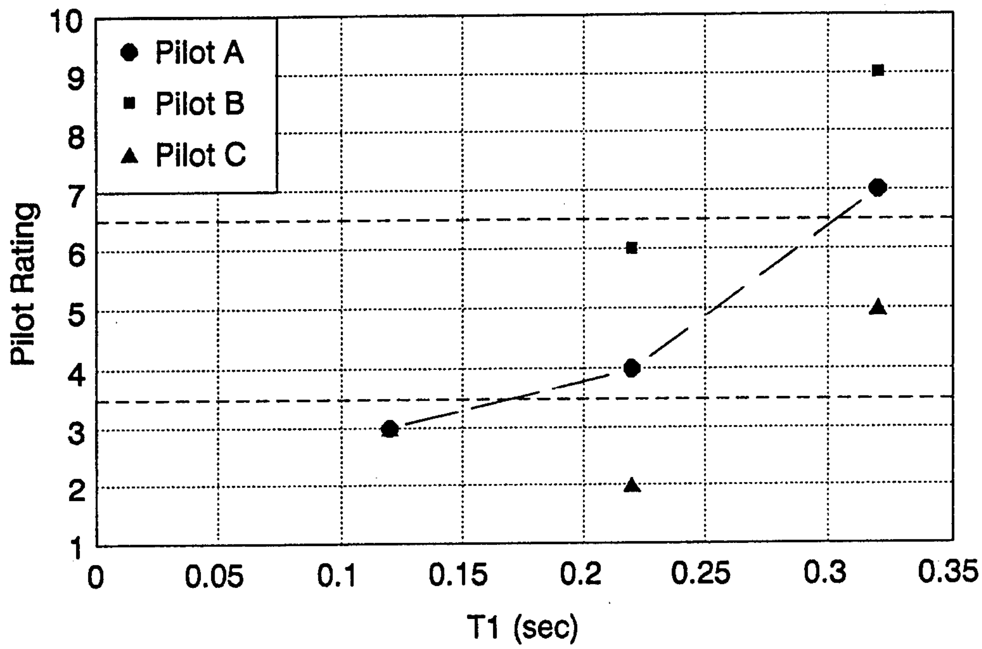


Figure 8(4.2.1.2). TIFS In-Flight Data, Nominal Stick Sensitivity (Time Delay Variation Cases) (from Ref. 35)

5. REQUIREMENT LESSONS LEARNED

Obviously, because of the importance of the requirements in this paragraph, there is an extensive lessons learned knowledge base. Coverage of all of these lessons is beyond the scope of this effort.

One important lesson learned in the course of this contract deserves some comment. Since the introduction of the "equivalent systems" concept, there has been considerable debate over the significance of the mismatch parameter. "Mismatch" is a mathematical measure of the "goodness of fit" of the LOES to the high-order system (HOS). The method for computing mismatch is defined in Appendix B of MIL-STD-1797A.

It has long been recognized (e.g., Refs. 36 and 37) that a high value of mismatch is associated with poor handling qualities. This observation was made based on equivalent-system fits to the Neal-Smith (Ref. 31) data base (as documented in Ref. 37), and it is also true for the LAHOS data of Ref. 32. As was shown in the Requirement Guidance discussion for this paragraph, however, attempting to apply the equivalent-systems approach to an inappropriate response type will also result in a high mismatch, even though the handling qualities may be excellent.

This suggests a possible new use for the mismatch parameter: Determination of the suitability of the equivalent systems approach for a given system. As an example, consider the mismatch values obtained

for the LAHOS data (for which the basic aircraft response was always conventional in form). The mismatch numbers for the LAHOS configurations are plotted against HQR in Figure 9 (circles). Also shown on this figure (+ and X symbols) are the mismatch values for the four example systems flown on the precision landing simulation study of Ref. 27 (see Figure 5 and Table 4). The following points can be observed from Figure 9:

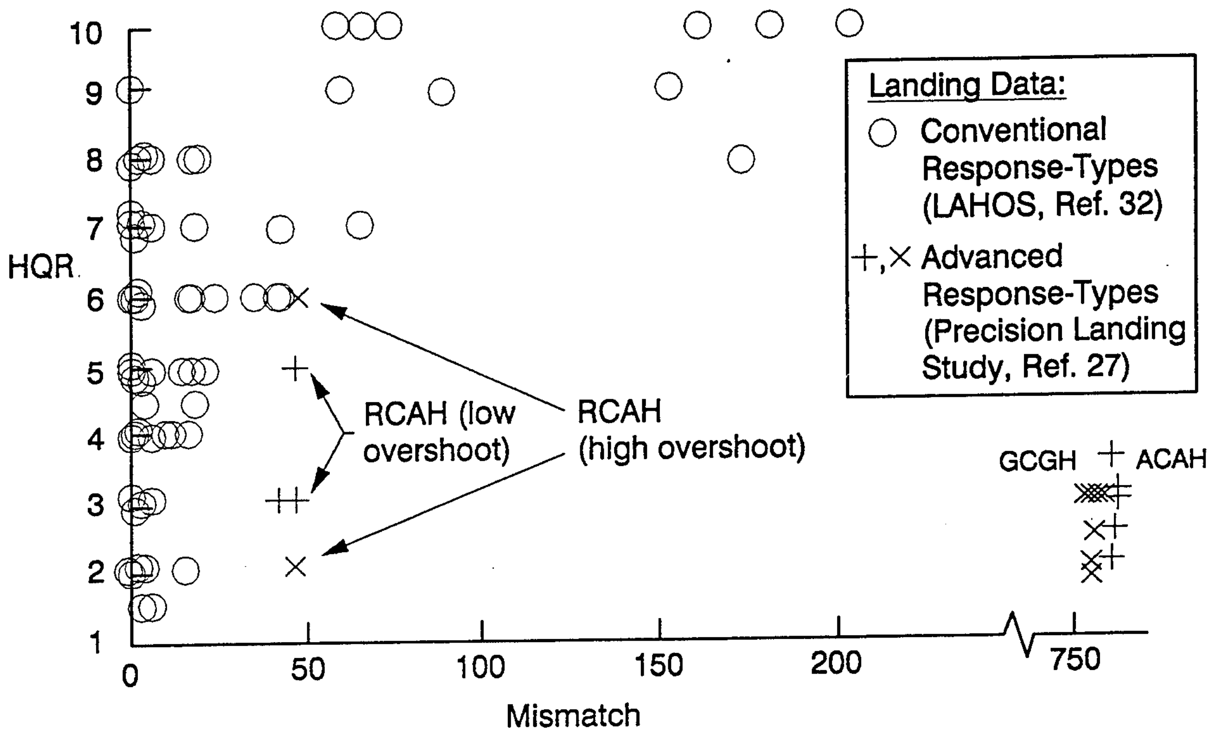


Figure 9(4.2.1.2). Handling Qualities *vs*. Equivalent System Mismatch ($1/T_{\theta_2}$ fixed)

- For the conventional response types (LAHOS data), it is possible to obtain a good match (mismatch near zero) for both good and bad systems. This is sensible, since a bad system should be as matchable as a good one, if there are no added dynamics to interfere with the matching process.

- Also for the conventional response types, a mismatch greater than 50 always corresponds to Level 3 handling qualities. This would suggest (as has been interpreted in the past) that a poor match is a sign of deficiencies in the airplane.

- For the non-conventional gamma command/gamma hold (GCGH) and attitude command/Attitude hold (ACAH) response types, a very high mismatch results, but the handling qualities were Level 1.

- For the rate command/attitude hold (RCAH) response types, mismatch was near 50 but the ratings are Level 1 or 2. These systems have much better HQRs than mismatch alone would suggest.

Based on the data in Figure 9, the following interpretation of mismatch is proposed: *a high level of mismatch (typically above 50) suggests that the equivalent systems approach is not appropriate for the given system.* In such a case, an alternative requirement such as Bandwidth must be used. It is possible, as Figure 9 shows, that a high mismatch is nothing more than a sign of bad handling qualities for a conventional response type. But the possibility that it is, instead, a sign of poor judgment in applying the equivalent-systems approach is too great to justify the risk.

4.2.1.3 Moderate-amplitude pitch response (attitude quickness) for aggressive Mission Task Elements

1. RECOMMENDED REQUIREMENT

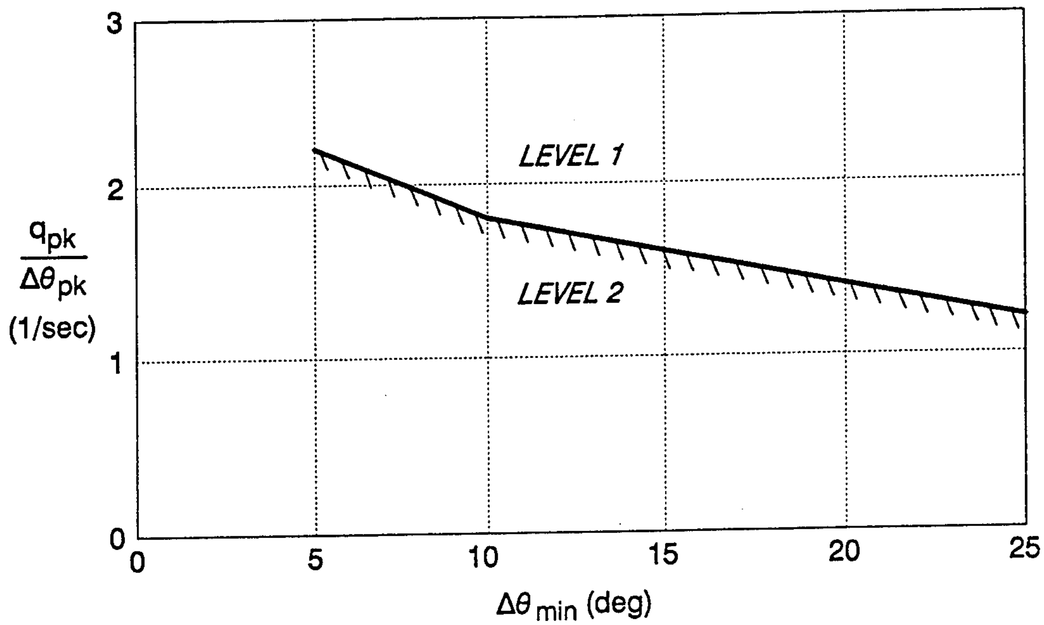
4.2.1.3 Moderate-amplitude pitch response (attitude quickness) for aggressive Mission Task Elements. *The ratio of peak pitch rate to peak change in pitch attitude, $q_{pk}/\Delta\theta_{pk}$ shall meet the limits specified in Figure 1a. The required attitude changes shall be made as rapidly as possible from one steady attitude to another without significant reversals in the sign of the cockpit control input relative to the trim position. The attitude changes required for compliance with this requirement shall vary from 5 deg to the limit of the Operational Flight Envelope or 25 deg, whichever is less. Parameters required for Figure 1a are defined in Figure 1b.*

2. REQUIREMENT RATIONALE

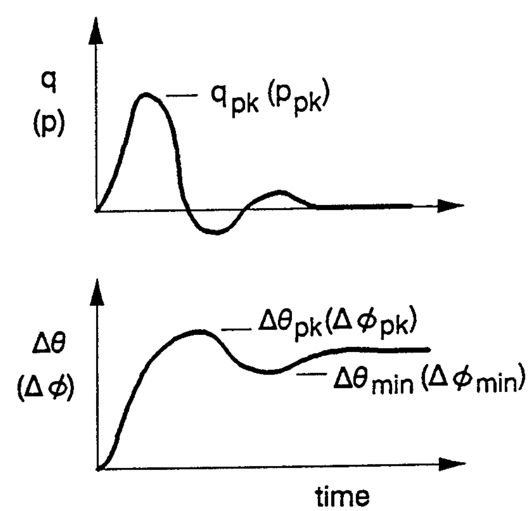
The parameter $q_{pk}/\Delta\theta_{pk}$ is related to Bandwidth, so this requirement effectively allows decreasing pitch attitude Bandwidth with increasingly large inputs. As the amplitude increases beyond small values, this interpretation becomes less appropriate, and the boundaries are better interpreted as a measure of agility. Failure to meet the limits often results from inadequate rate limits on the pitch control surface actuator that can lead to pilot-induced oscillations. The requirement is intended to apply above the attitude changes normally associated with fine tracking.

3. REQUIREMENT GUIDANCE

This is a new requirement for MIL-STD-1797A. It is not, however, a new requirement in the flying qualities world: the principles were originally developed for helicopters (Ref. 38) and the requirement was incorporated into the U.S. Army's rotorcraft specification, ADS-33C (Ref. 5) in 1989. The derivation of the attitude quickness criterion, and specific guidance on its application, are given in the guidance for the roll counterpart, 4.5.1.6. Because the supporting data for this requirement (discussed below) come from a simulation of a target acquisition task, the requirement itself has been restricted to aggressive maneuvering only. This specifically means the Mission Task Elements contained in new Categories A and D.



a) Requirement (Categories A and D)



b) Definition of Parameters

Figure 1(4.2.1.3). Requirement for Moderate-Amplitude Pitch Response (Attitude Quickness) for Aggressive Maneuvering

4. SUPPORTING DATA

The basis for the Level 1 limit shown in Figure 1a is the simulation conducted in support of this contract. A summary of the simulation is given in Appendix A. Detailed analysis of the results of the simulation, as appropriate for the military standard, is presented in the guidance for 4.5.1.6. Following is a review of the pitch results as applied to this requirement.

The simulation focused primarily on roll attitude quickness requirements with a large matrix of variations in roll response dynamics. For pitch, the only response type evaluated was a basic rate-augmented system. Variations in pitch attitude quickness were made entirely by changing the rate limits on the simulated elevator actuator. The dynamics of the actuator were set very high (second-order filter with a natural frequency of 75 rad/sec) to minimize the effects of the basic actuator dynamics on pilot ratings. The best roll dynamics were used for all the pitch evaluations. Task details were identical to those used for the roll variations (see Appendix A); five pilots evaluated pitch actuator rate limits of infinity and 80, 40, and 20 rad/sec. Four of the pilots flew all cases, with several evaluating some cases more than once.

Construction of the limit drawn in Figure 1a followed the format developed in Ref. 39. Attitude quickness was calculated for pitch attitude changes of 5, 10, 15, 20, and 25 deg, using ideal inputs and models of the test configurations. Average Cooper-Harper Handling Qualities Ratings (HQRs, Ref. 3) were crossplotted against the ideal attitude quickness for each configuration at each pitch attitude, as shown in Figure 2. Only one of the pitch cases (with a 20-deg/sec rate limit) received Level 2 average ratings, though the next lowest case (40 deg/sec limit) was considered to be Level 2 by two of the five pilots.

These data are obviously very limited and must be augmented by more simulation, or, preferably, flight data. The limit drawn is considered, however, to be a good first cut, based in part on the success of the roll analysis and the similarities of the resulting Level 1 limits. It is conceivable that, given a requirement to pitch through larger attitude changes, the limits in Figure 1a may prove to be too lenient. They are not expected to ever be too conservative, however, so their adoption should help insure good moderate-amplitude flying qualities.

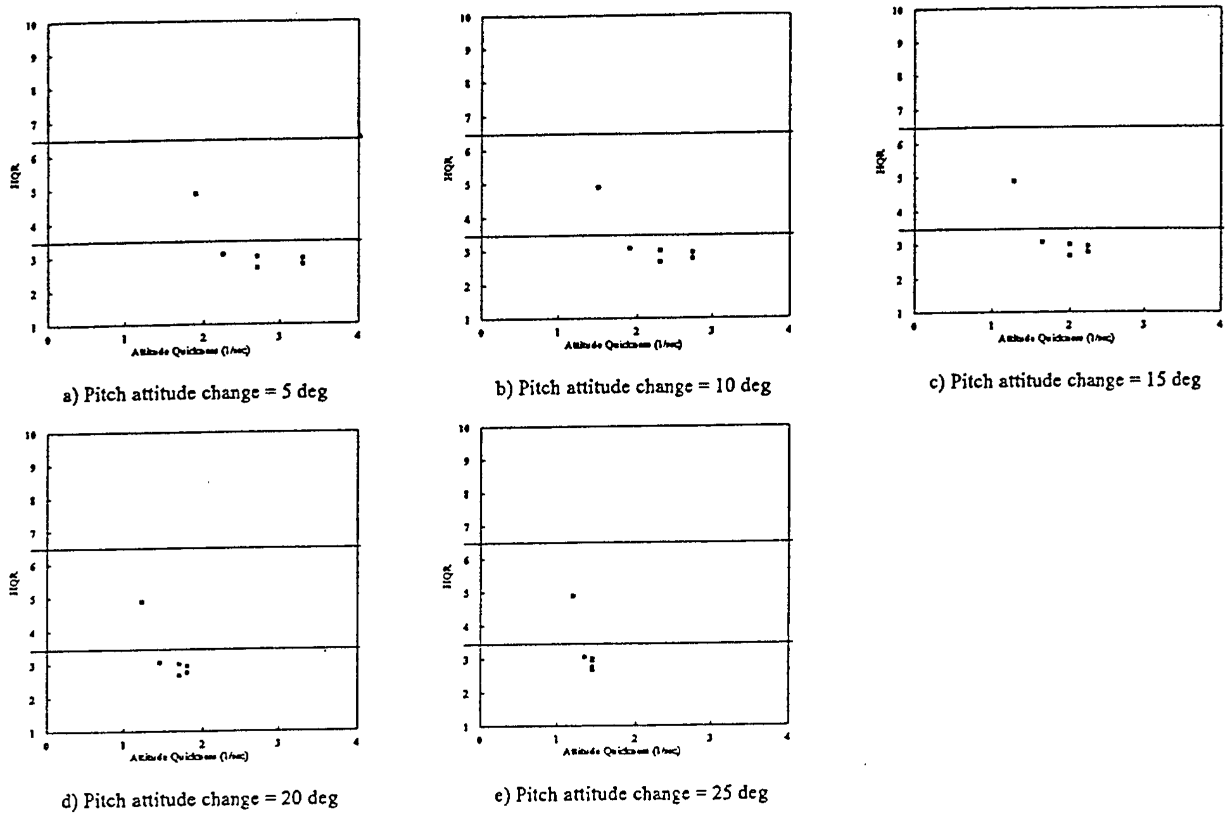


Figure 2(4.2.1.3). Average Handling Qualities Rating *vs.* Ideal Attitude Quickness in Pitch for Pitch Variation Cases from Simulation (Appendix A)

5. REQUIREMENT LESSONS LEARNED

Since this is a new requirement to fixed-wing airplanes, there are no specific lessons learned to be discussed. There are, however, significant lessons from the application of the attitude quickness requirements to helicopters. Some of these lessons are given for 4.5.1.6.

4.2.2 Pilot-in-the-loop pitch oscillations

1. RECOMMENDED REQUIREMENT

4.2.2 Pilot-in-the-loop pitch oscillations. The pitch attitude response dynamics of the airframe plus control system shall not change abruptly with the motion amplitudes of pitch attitude, pitch rate, or normal acceleration unless it can be shown that this will not result in a pilot-induced oscillation. *For Flight Phase Categories A and D the following shall apply, with the cockpit control feel system included as a part of the aircraft:*

a) *The pitch attitude phase delay parameter, $\tau_{p\theta}$, shall be less than 0.19 seconds.*

b) *If the pitch attitude Bandwidth frequency, ω_{BW_θ}, is less than 1 rad/sec, the aircraft shall meet the pitch rate overshoot versus pitch attitude dropback limit of Figure 4(4.2.1.2).*

For Flight Phase Categories B and C the following shall apply:

a) *The pitch attitude phase delay parameter, τ_{p_θ}, shall be less than 0.15 seconds if either the pitch attitude Bandwidth (4.2.1.2) or the flight path Bandwidth (4.3.1.1) is not Level 1.*

b) *If the pitch attitude Bandwidth frequency, ω_{BW_θ}, is less than 1 rad/sec, the aircraft shall meet the pitch rate overshoot versus pitch attitude dropback limit of Figure 4(4.2.1.2).*

2. REQUIREMENT RATIONALE

Pilot-in-the-loop (or more commonly pilot-induced) oscillations are the results of poor handling qualities. While meeting other handling qualities requirements, primarily those on short-term pitch and flight path response, should (in the absence of nonlinearities, such as actuator rate limiting) prevent any potential for PIOs, there is a need for an explicit criterion to test for the tendency for catastrophic PIOs, especially in the event that the other requirements cannot be met.

3. REQUIREMENT GUIDANCE

PIOs are not new. There has been a recent increase in interest in PIOs as a result of several well-publicized incidents with advanced aircraft such as the USAF YF-22 and the Swedish Saab Gripen. With the regular use of high-gain, full-authority, fly-by-wire flight control systems, the potential for PIO has become greater. Because of this concern over the occurrence of PIOs, it has become imperative that some form of metric be defined to allow for the accurate prediction of the potential for catastrophic PIOs.

Several alternative forms of such metrics currently exist, including those in MIL-STD-1797A, and others proposed for incorporation into a future version of the military standard. As a part of the effort to develop mission-oriented flying qualities, a review of the proposed criteria, the Smith-Geddes criteria, was undertaken. In addition, a separate analysis was performed of the effectiveness of the Bandwidth criteria at predicting PIO tendencies. The results of both reviews, which are lengthy discussions in themselves, are presented in Appendix E of this report. Before reading the quantitative discussions in Appendix E, however, the following general background information should be read first.

a. Definition of PIO

There are many types of pilot-in-the-loop oscillations. It is important to recognize what we mean by a PIO, so that we can differentiate between annoying limit cycles and the catastrophic, explosive oscillations that can potentially lead to loss of the aircraft. MIL-STD-1797A contains a concise definition:

"sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft." Taken literally, this means that *any* oscillation that occurs during manual, piloted control may be classified as a PIO. Yet many times this oscillation is nothing more than a result of pilot overcontrol in an otherwise normal circumstance. For example, to the outsider the typical ballooning in flight path that any student pilot encounters during landing training may appear to be a PIO. Yet this ballooning is simply part of standard pilot compensation and is usually no more than one or two cycles, with no threat of developing into a real PIO. Indeed, visual inspection of the time history records from even the experienced pilot in the landing flare with a known good airplane will reveal small corrections that might appear to be signs of a PIO. These are *not* what MIL-STD-1797A is referring to.

PIOs may generally be divided into two basic frequency regimes as follows.

- <u>Oscillations near the frequency for closed-loop piloted control.</u> Dangerous PIOs occur at frequencies around the pilot's crossover frequency. It is shown below that the frequency for such PIOs is near the airplane's attitude neutral-stability frequency.

- <u>High-frequency oscillations.</u> Oscillations well above the frequency for piloted control with different names and general characteristics for pitch and roll:

  <u>Pitch bobble:</u> Often, with highly-augmented airplanes and in tight, precision tasks (such as final landing flare), there will be pilot complaints of pitch "bobble," or a tendency for high-frequency, small-amplitude oscillations, primarily in pitch attitude and rate. Pitch bobble occurs at frequencies well above normal closed-loop control, generally around 10 rad/sec or greater. The oscillations are more of a nuisance that detract from ride qualities, and hence degrade handling qualities. Such oscillations will lead to pilot comments about some potential for PIO, but there is no evidence that they will, directly, result in a catastrophic PIO.

  <u>Roll ratchet.</u> This is the roll counterpart to pitch bobble. Roll ratchet also occurs at frequencies above 10 rad/sec and may be due to interactions between the airplane, the cockpit controller, and the pilot's neuromuscular system (Ref. 40). As with pitch bobble, it is a nuisance to the pilot but does not normally lead to a divergent PIO.

To be effective at predicting PIOs, any criterion must be capable of differentiating between non-destructive and destructive PIOs.

b. PIOs and Handling Qualities

With the intense focus on PIOs and their prevention, there is sometimes a perception that PIOs are unique phenomena for which conventional handling-qualities engineering has failed to account. This is not the case. While it is true that MIL-STD-1797A does not directly address PIOs explicitly to any large

degree, it is not because of a failure of the criteria. Instead it is a result of an underlying assumption: that PIOs are a manifestation of deficient handling qualities. If an aircraft meets all of the Level 1 requirements (that is, requirements that specify "satisfactory without improvement"), it is assumed that a PIO is not likely to occur. If the aircraft fails some well-defined criterion, especially if it is Level 3 in terms of the criterion, a PIO is very likely, but is not guaranteed. In this case, the PIO is just one of many possible signs of deficient handling qualities.

c. Do We Need a Separate PIO Criterion?

If PIOs are one sign of degraded handling qualities, and hence are not, in a handling qualities sense, unique phenomena, do we need a separate PIO criterion?

Experience has shown that schedule and cost constraints nearly always result in compromises during the development of the flight control systems of modern aircraft. These compromises typically result in degradations in aircraft handling qualities, and therefore failure to meet the stringent Level 1 limits. Most (if not all) current highly-augmented aircraft do not meet all of the Level 1 limits of MIL-STD-1797A, and are not considered to be Level 1 for all mission tasks. Typical problems are slow actuators, stick filters necessitated by the use of force transducers, bending mode filters, anti-aliasing filters, computational time delay, excessive parallel integrator gains, and improper flight control system design.

The problem is amplified by the fact that the use of active control technology often results in a significant modification of bare airframe response characteristics. For example, the unaugmented X-29A doubles amplitude in well under one second, and is completely uncontrollable by the pilot. The augmented aircraft is well-damped with a crisp response characteristic. This requires control power. Control power has classically been achieved with increased control surface sizing. This is, however, in direct conflict with the primary performance objectives that led to active control design in the first place. The result is smaller surfaces that must move very rapidly. This stresses the actuators, resulting in lags and rate limiting as an inherent problem in the design. Hence, it is not surprising that we have seen many PIOs in highly-augmented aircraft. Strict adherence to the flying qualities specification could result in excessively large control surfaces. Clearly, we need a criterion that allows the tradeoff between performance and handling qualities to be made with a firm understanding of the inviolable PIO limits.

If we accept the basic premise that Level 2 handling qualities are good enough to accomplish the mission, albeit with increased pilot workload, then it is inevitable that in the context of the above tradeoffs between performance and handling, plus the usual budget and schedule crises, Level 2 can be acceptable. This has been a fact of life for all modern aircraft development programs. Given the adaptability of the

human pilot, and the proper "can do" attitude of professional and military pilots, the Level 2 aircraft is an acceptable compromise and gets the job done. When the deficiency that causes the aircraft to fall in a Level 2 region has a potential for a catastrophic PIO, however, its impact is far more dangerous than simply the increased pilot workload. Therefore, it is important to make a distinction between deficiencies that cause a flying qualities parameter to predict Level 2, and one that can result in a divergent PIO.

d. The Elements of the PIO

In a global sense, the players in the development of PIOs may be divided into three elements (Ref. 41): the airplane, the pilot, and the trigger. For the purposes of this discussion, consider the airplane as consisting of three separate elements: the linear augmented airplane, the control surface actuators, and the cockpit control feel system.

The Dynamics of the Linear Airplane. — Experience has shown that the dynamics of the augmented linear airplane are usually responsible for divergent PIOs. It has been suggested that very low actuator rates on an otherwise good airplane may also lead to PIOs. This is discussed further below. The dynamics of the airplane are what the flying qualities requirements are intended to address. Whether the cockpit feel system should be included in these dynamics is examined below.

With full-authority augmentation systems, it has become relatively straightforward to provide modern airplanes with a reasonable level of basic short-term dynamics, *in the absence of significant time delays*. With advanced control systems, there are three forms of added complexity that serve to degrade the flying qualities of the augmented airplane: 1) time delays from computer frame time and sample rate, resulting in a rolloff in phase angle between control input and airplane response at high frequencies; 2) filters on the stick, for bending modes, etc., that also contribute to phase rolloff; and 3) unavoidable lags, such as those due to the actuator, that *also* introduce phase rolloff.

To be successful, any criterion used to predict PIOs must be sensitive to this high-frequency phase rolloff in aircraft response. It was the motivation for developing the phase delay parameter in the Bandwidth criteria, and it is the phenomenon that is captured (with varying degrees of success) by equivalent time delay when equivalent-systems criteria are applied. The phase rate parameter developed by Gibson in Great Britain (Ref. 29) also defines the effects of phase rolloff; when measured over the same frequencies, phase rate is identical in form to phase delay. Any criterion that does not directly address the high-frequency rolloff of phase angle must be considered incomplete. (It is important to note that phase delay is *not* a measure of time delay *per se*. It is a measure of the shape of the phase response

of angular attitude to control inputs above the neutral-stability frequency, of which time delay is only one factor.)

When properly defined and applied, conventional flying qualities criteria are sufficient to identify the expected Level of flying qualities for the linear augmented airplane. Further determination of PIO potential, and the type and severity of the PIO, requires new criteria, or a refinement to existing ones.

The Control Surface Actuator. — Any physical object has mass and inertia. As a consequence there must be some limit to the capabilities of the system to generate accelerations, rates, and positions, no matter how hard the system is pushed. With the use of high gains and small control surfaces, great demands are placed on the airplane's surface actuator to achieve as rapid a response as possible. Sometimes, there will be an incompatibility between the demands of the control system and the capability of the actuator, and a rate limit will result.

It seems to be true that all recent PIOs have exhibited actuator rate limiting. It is also true that all of these PIOs have been with aircraft that have poor flying qualities to begin with. Therefore, it is not possible to determine if rate limiting of the actuator is the *cause* of the PIO, or simply an *effect* of it.

Recent research by Chalk at Calspan and others has suggested that a PIO can occur with rate limiting even for an otherwise good airplane. Signs of this behavior were observed during an in-flight experiment on the USAF/Calspan Total In-Flight Simulator (TIFS), investigating advanced control laws for a proposed large airplane. It appears that no such PIO has actually ever occurred for any operational airplane — primarily because few modern operational airplanes possess good inherent flying qualities. Similarly, there is no documented incident where an airplane with poor flying qualities and a high-frequency actuator suffered a PIO without rate limiting.

Clearly more work is justified in this area. It should be possible to define the response requirements for the actuator, in terms of handling qualities, that will protect against PIO. For now, their linear characteristics are included as a part of the linear airplane dynamics, and the effect of their rate limits on PIOs is a subject for speculation.

The Cockpit Control Feel System. — There is currently some disagreement on the influence of the feel system on handling qualities, and therefore on PIOs. As discussed earlier in this report, however, it is clear that the feel system is an integral part of the aircraft, and will, therefore, have some effect on the potential for PIOs.

The Pilot. — The dynamics of the human operator in manual closed-loop control are well-known from the works of researchers at STI (Ref. 22). There is much less certainty about the pilot's characteristics

during a PIO, however. A model based on the "synchronous" pilot has been proposed (Ref. 42). Essentially this model assumes that the pilot develops no compensation and exhibits no effective lags or delays, instead reacting synchronously with visual information to generate a sinusoidal response. This model has been disputed by R. Smith (Refs. 43 and 44), among others, who usually suggest that the pilot reacts more to the sensation of linear accelerations, or to a combination of visual and motion information depending upon a number of factors.

The Trigger. — A key catalyst in the occurrence of a PIO is a trigger mechanism. Typically this is a requirement for a rapid change in the pilot's control strategy during an otherwise normal task. For the precision landing, for example, it can be a sudden gust, a wind shear, or the demands of the landing flare itself, as the pilot attempts to touch down within a target zone. It is important to recognize that the trigger does not *cause* the PIO: bad flying qualities are to blame. For airplanes that have acceptable flying qualities for otherwise benign maneuvering, a trigger is necessary simply to force the pilot into control behavior that induces an oscillation.

Other Contributors — For most PIOs encountered by modern aircraft, there are several other contributing factors that increased the propensity for handling qualities problems. These factors are, therefore, contributors to the flying qualities of the airplane, but their effects are not generally sufficiently well known to include them as part of the linear airplane. Included in this category are unconventional controllers (sidesticks, mini-sticks, etc.) with unusual control/deflection characteristics, force sensing, etc.; and control/response sensitivities that are excessive or excessively nonlinear with input amplitude. Many of these contributors are *addressed* by MIL-STD-1797A, but what constitutes good and bad characteristics are not thoroughly *defined* by the standard.

4. SUPPORTING DATA

Supporting data for this requirement, as well as a detailed analysis of the Smith-Geddes criteria, are presented in Appendix E.

5. REQUIREMENT LESSONS LEARNED

The continuing occurrence of PIOs indicates that a requirement for their prevention is sorely needed. The Smith-Geddes PIO criteria have been reported to be extremely effective at predicting PIOs on prototype and operational aircraft at Edwards AFB. Unfortunately, little quantitative evidence of this effectiveness is available.

There is, in general, an unfortunate lack of accurate documentation of the dynamic characteristics of most currently operational airplanes. A careful analysis of every PIO incident, *and* of the dynamics of airplanes that show no tendency to PIO, should be performed. As an example application of both the Smith-Geddes and Bandwidth PIO criteria, the predictions for two airplanes are presented and compared with practical experience.

The T-38A PIO. — In 1960, a T-38A suffered a violent pitch PIO in low-altitude transonic flight, with oscillations in normal acceleration as high as -9 to +8g. This incident has been thoroughly analyzed (Ref. 42); a major contributor was found to be a nonlinear bobweight in the pilot's control loop.

Using the transfer functions given in Ref. 42, with the bobweight loop open (the pre-PIO condition), for the Smith-Geddes criterion the criterion frequency is $\omega_c = 5.4$ rad/sec, and the resulting pitch attitude phase angle is $\angle\theta/F_{es}(j\omega_c) = -109°$. Since this is well below the PIO limit of -165°, the Smith-Geddes criterion predicts no PIO. When the bobweight loop is closed (corresponding to the PIO), $\omega_c = 5.5$ rad/sec, and the pitch attitude phase angle actually improves to $\angle\theta/F_{es}(j\omega_c) = -65°$. Hence the Smith-Geddes criterion predicts no PIO for this condition as well, and in fact predicts an improvement in flying qualities.

For the Bandwidth criterion, with the bobweight loop open the phase delay $\tau_{p\theta} = 0.118$ sec — close enough to the PIO limit of 0.12 sec to be concerned. The dropback and Bandwidth frequency requirements are met, so no pitch bobble is predicted. Closing the bobweight loop increases $\tau_{p\theta}$ to 0.143 sec — enough for a PIO. In addition, the dropback in this case is excessive, so pitch bobbles are also predicted, increasing the likelihood of a PIO.

The F-15 in Landing. — It may not be possible to define precisely what a "PIO-proof" airplane is, but based on discussions with Air Force pilots, it has been suggested that the F-15 is a good representative. Reportedly there is no tendency for PIOs or bobble in landing, so PIO should *not* be predicted for this airplane. Transfer functions for an F-15 in landing configuration at 134 KCAS were obtained from an unpublished source.

For the F-15, CAS on, the Smith-Geddes criterion frequency $\omega_c = 3.2$ rad/sec, giving $\angle\theta/F_{es}(j\omega_c) = -182°$ — thus predicting PIO susceptibility.

Based on Bandwidth, $\tau_{p\theta} = 0.077$ sec with low dropback — thus predicting *no* PIO susceptibility, confirming the pilot comments. (It is interesting to note, however, that the Bandwidth frequency is low enough to indicate Level 2 handling qualities for the F-15. In a recent flight experiment conducted by

the USAF Test Pilot School, the results of which are not yet published, the average HQR for the F-15 from 17 evaluations was 3.7, or Level 2, in agreement with the Bandwidth limit.)

Because all of the problems of the T-38A were at frequencies well above the Smith-Geddes criterion frequency, the possibility of a PIO would not be detected. And because the dynamics of the F-15 are low-frequency — typical of any airplane, unaugmented or augmented, when operating at landing speeds — the conservative nature of the Smith-Geddes criterion results in a prediction of PIO tendencies. By contrast, the primary factor in the Bandwidth criterion for predicting PIOs — phase delay — is a measure of phase rolloff wherever it occurs, and this criterion successfully predicts the PIO characteristics of both aircraft.

4.2.7 Pitch axis control power

4.2.8 Pitch axis control forces

DISCUSSION

As a part of this effort, a review of all of the pitch (and roll) control force requirements was conducted for sidestick controllers. Specific limits have been proposed for most of the control force requirements that fall under 4.2.8. A summary discussion, with recommended changes to the force limits in the military standard, is presented as Appendix D to this report. Further work is justified to verify these limits and to determine if distinctions based on aircraft Class can be eliminated.

4.3 Flying qualities requirements for normal (flight path) axis

4.3.1 Flight path response to attitude change

4.3.1.1 Transient flight path response to attitude change

1. RECOMMENDED REQUIREMENT

4.3.1.1 Transient flight path response to attitude change. The relation of the flight path response to pitch attitude, for pilot control inputs, shall be as follows:

a. *The flight path Bandwidth frequency shall meet the requirements of Figure 1. Flight path Bandwidth is defined as the frequency at which the response of flight path angle, measured at the aircraft center of gravity, lags the cockpit control input, including the feel system, by 135 degrees.*

b. If a designated controller other than attitude is the primary means of controlling flight path, the *flight path Bandwidth can degrade to Level 2.*

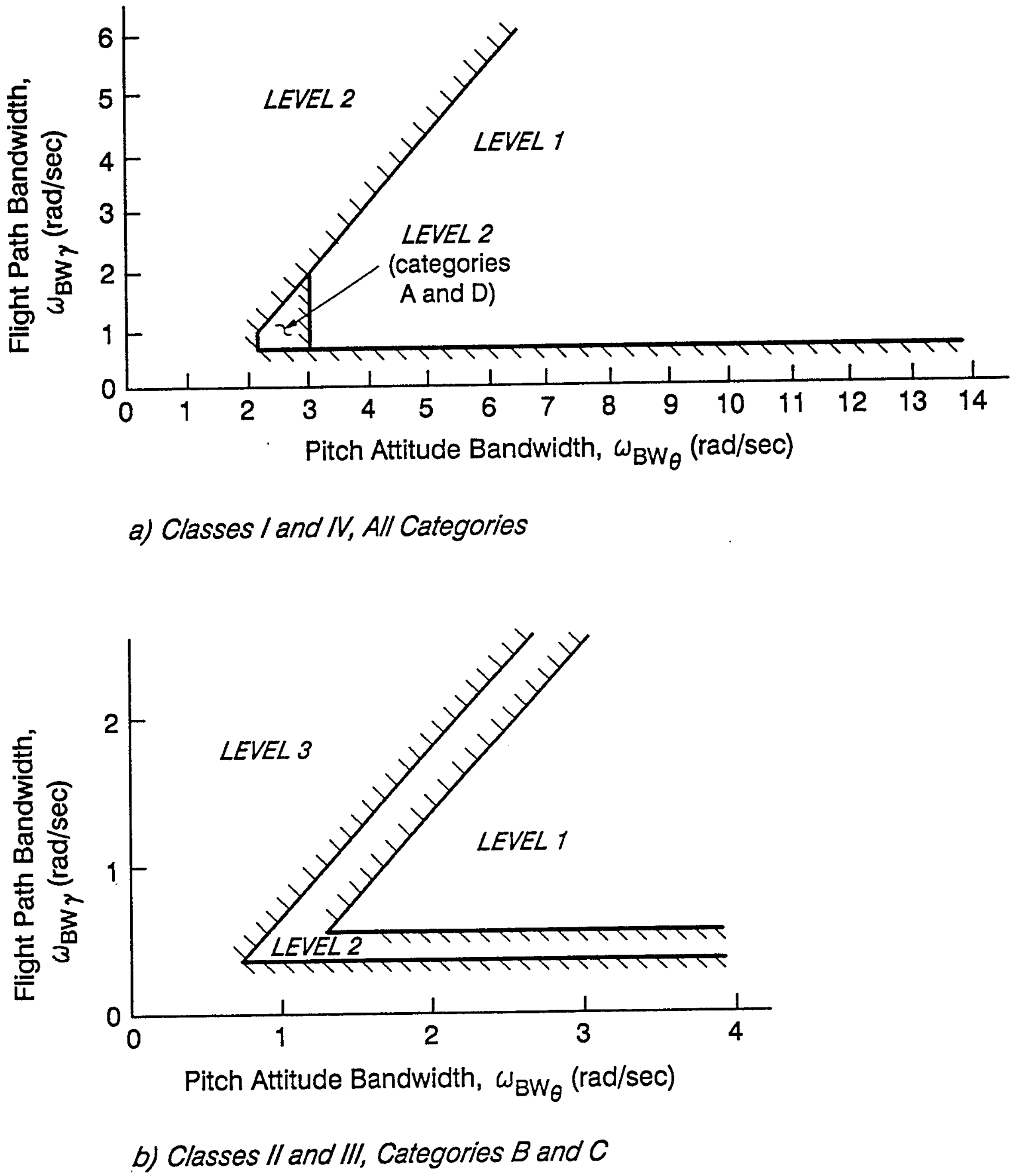


Figure 1(4.3.1.1). Limits on Transient Flight Path Response to Attitude Change

2. REQUIREMENT RATIONALE

This requirement is intended to insure that the consonance between flight path and pitch attitude is consistent with the pilot's expectations. When pitch attitude is the primary short-term controller of flight path, excessively abrupt or sluggish flight path response to attitude changes will cause problems for precise control and possibly lead to pilot-induced oscillations. If the path response to attitude is not adequate a separate controller should be provided.

3. REQUIREMENT GUIDANCE

Requirements on flight path Bandwidth for transports have been under development for several years. The initial work was performed in the mid-1980's as a part of a development effort for STOL handling qualities criteria (Ref. 45). The requirements have evolved to their present state where, in combination with criteria on pitch attitude Bandwidth on pitch rate overshoot/pitch attitude dropback, they are extremely effective at predicting handling qualities. Supporting data for these requirements are presented in Appendix E.

If a separate flight path controller is available a degradation in flight path Bandwidth can obviously be tolerated. The question is, how much? It may be argued that, with an effective means of directly controlling flight path (i.e., a controller that meets the requirements of 4.3.2), there is no need to have any flight path Bandwidth. There is no real evidence that this is true, however, and it seems that a more conservative approach is warranted for two reasons. 1) Sometimes, even with a direct control of flight path, pitch attitude will be used by the pilot for minor corrections in flight path. In such a case, there should still be adequate (i.e., Level 2) consonance between attitude and flight path. 2) In the event the designated flight path controller is not Level 1 by 4.3.2, the pilot is certain to attempt to control flight path with pitch at some time during the operational lifetime of the airplane. Level 2 flight path Bandwidth will provide some response, and will hopefully protect against more severe consequences of incorrect control technique.

It is important to note that this requirement does not specifically address the *magnitude* of the flight path response to attitude changes: it is possible to have good flight path Bandwidth but inadequate long-term power.

4. SUPPORTING DATA

See Appendix E.

4.3.2 Flight path response to designated flight path controller

1. RECOMMENDED REQUIREMENT

4.3.2 Flight path response to designated flight path controller. When a designated flight path controller (other than the pitch controller) is used as a primary flight path controller, the short-term flight path response to designated flight path controller inputs shall *meet the requirements of Figure 1.* At all flight conditions the pilot-applied force and deflection required to maintain a change in flight path shall be in the same sense as those required to initiate the change.

2. REQUIREMENT RATIONALE

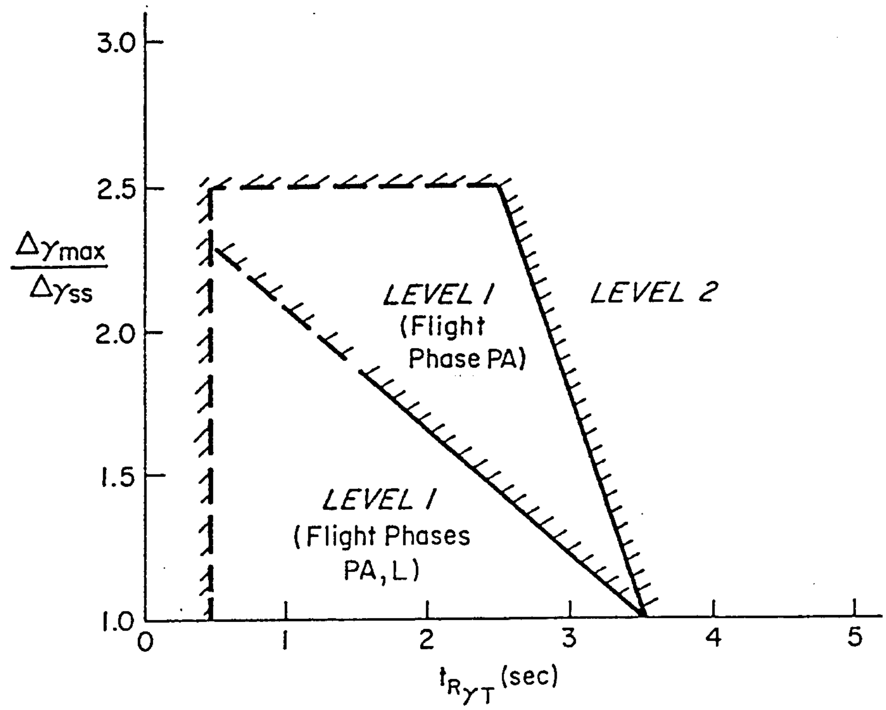
These requirements are intended to be the primary flight path control criteria for STOL aircraft. These aircraft operate well on the back side of the power-required curve and therefore use a designated controller other than pitch attitude (such as throttle) to control flight path.

3. REQUIREMENT GUIDANCE

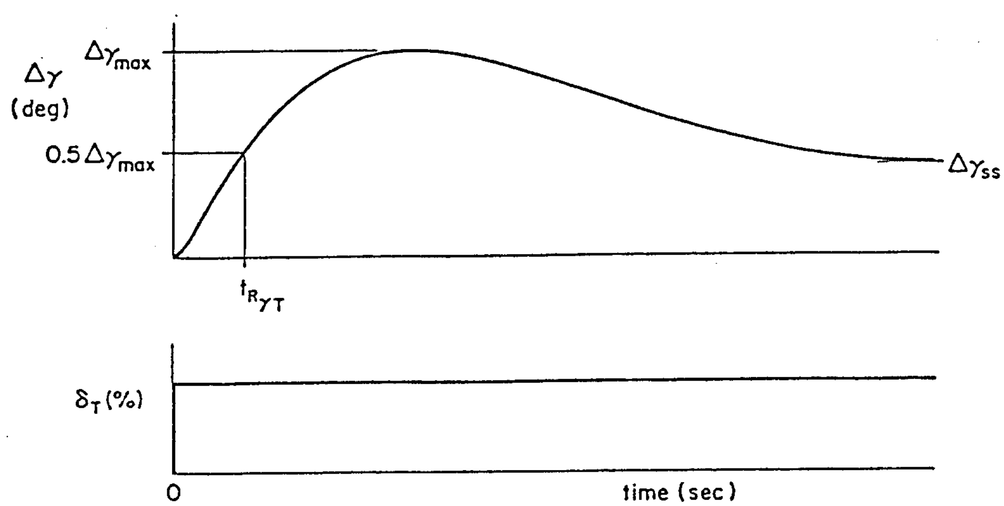
There was an intense flurry of activity on STOL handling qualities and airworthiness in the 1970's. Most of this was focused toward civil STOL transports. In the mid-80's a second, smaller effort was undertaken in parallel with the initial groundwork for the F-15 S/MTD aircraft. The recommended requirement was originally developed in the early STOL activity, then refined to its present state in the later work.

4. SUPPORTING DATA

The requirement, its definition, and all supporting data can be found in both Refs. 45 and 46.



a) Requirement



Note: Pitch attitude controller is free during response

b) Definition of Parameters

Figure 1(4.3.2). Level 1 Limits for Short-Term Flight Path Response to Step Input of Designated Flight Path Controller

4.5 Flying qualities requirements for the roll axis

4.5.1 Roll response to roll controller

4.5.1.1 Roll mode

4.5.1.1.1 Roll attitude Bandwidth for Class IV aircraft

1. RECOMMENDED REQUIREMENT

4.5.1.1 Roll mode. The equivalent roll mode time constant, T_R, shall be no greater than *that required in Table XXIV.*

4.5.1.1.1 Roll attitude Bandwidth for Class IV aircraft. *For Class IV aircraft roll Bandwidth, ω_{BW_ϕ}, shall be at least 1 rad/sec for Level 1. Phase Delay, τ_{p_ϕ}, shall be no more than 0.14 sec for Level 1 and 0.20 sec for Level 2. This requirement applies for all Mission Task Elements, and it also replaces 4.5.1.5, roll time delay, for Class IV aircraft. The cockpit control feel system shall be included in all measurements.*

2. REQUIREMENT RATIONALE

The roll Bandwidth requirement is proposed as a first step in providing a more comprehensive criterion for advanced aircraft. For most aircraft, the basic limits on T_R will be sufficient. If augmentation were used to produce an unusual response type that is not well addressed by T_R, the Bandwidth limits are a suitable alternative. Since the Bandwidth requirement includes Phase Delay directly, there is no need to apply the roll time delay requirement of 4.5.1.5.

3. REQUIREMENT GUIDANCE

The requirement on roll time constant is unchanged from MIL-STD-1797A. The listing of Flight Phase Categories in Table XXIV of MIL-STD-1797A will require revision to reflect the new proposed Categories. A requirement on roll Bandwidth is a sensible addition to the military standard. Unfortunately, at this time there is only meager information on the requirements for roll Bandwidth, so the limits of this requirement should be considered tentative. These limits were derived from flight research data for Class IV airplanes (see Supporting Data) and hence are to be applied only to such airplanes for now.

4. SUPPORTING DATA

In recent years two major studies of roll control requirements for Class IV aircraft have been performed by Calspan using the variable-stability NT-33A. These are the so-called LATHOS study (Ref. 47) and the feel system study (Ref. 26). Unfortunately, because neither experiment was specifically designed to look at roll Bandwidth, the test plans were not devised to provide a wide range of variations in the most important parameter — roll mode time constant. The data may be used for the examination of Bandwidth requirements, but it must be recognized that the range of roll time constants evaluated did not cover Levels 1, 2, and 3 as stated in MIL-STD-1797A.

In addition, and most critically, both experiments included roll control sensitivity as a variation parameter as well. Hence, the pilots were not able to select roll sensitivity. As a consequence, it is difficult at times to identify the individual contributions of roll time constant, sensitivity, added dynamics (lags and filters), and feel system dynamics on pilot opinion. For example, as is shown below, there are many configurations with very poor pilot ratings that should have gotten good ratings based on their Bandwidth and Phase Delay parameters. The poor ratings may then be attributed to control sensitivity.

A preponderance of Level 2 and 3 ratings was found in both experiments, including cases for which Level 1 ratings might have been anticipated based upon aircraft dynamics. This is not surprising considering several experimental design details, in addition to the sensitivity issue discussed above:

- No control system friction or breakout forces were included. A breakout force of zero is Level 3 by the requirements of 4.5.9.4 in MIL-STD-1797A.

- The lateral stick force/deflection gradients used for most of the evaluations, F_{as}/δ_{as} = 3.4-4 lb/in., were probably marginally excessive, especially for the more responsive configurations. For example, in the Ref. 26 experiment a configuration that was rated a 7 by one pilot with F_{as}/δ_{as} = 4 lb/in. was reflown with F_{as}/δ_{as} = 2.75 lb/in. and was rated 2 and 3 by the same pilot.

- Control sensitivity, which was varied in the Ref. 47 study, was not varied as much in Ref. 26, but the results are significant. For example, most configurations in Ref. 26 flown with a roll mode time constant of 0.25 sec also had a steady-state roll gain of 18 deg/sec/lb, and the best rating obtained for any such case was an HQR of 5. By contrast, one case was flown with a gain of 10 deg/sec/lb, and was rated 2 and 4 by one pilot. This suggests that 18 deg/sec/lb was probably too high for all of the cases. As a result, it is not possible to use these 0.25-sec cases in this analysis.

These design details do not invalidate the results of the experiments, but they make their interpretation more difficult.

In the case of the Ref. 26 feel system study, it is appropriate to eliminate the ratings from one of the three pilots (identified in Ref. 26 as Pilot B). As discussed in Ref. 19, the ratings from this pilot are not highly correlated with those of the other two pilots, or with the variations in response dynamics.

Similar interpretation of the LATHOS data of Ref. 47 is required. In this experiment the range of control sensitivities tested was greater; in those cases where multiple gains were flown, the best pilot ratings were selected for this analysis. In some cases all ratings are either good (suggesting that all aspects of the aircraft were good) or bad (suggesting that either the dynamics are bad, or a good control sensitivity was not used for this case).

In addition, it was decided, based on discussions presented elsewhere in this report, that the effects of the cockpit feel system would be included in all calculations. This is significant since the LATHOS experiment used force sensing (which normally means the feel system is ignored) and the feel-system study evaluated both force and position sensing (in the latter instance the feel system is normally included). While it is recognized that the effects on pilot opinion of the lags due to the cockpit feel system are *not* the same as the effects of a lag elsewhere in the aircraft, it is shown in Ref. 19 and in this report that the feel system is *not* transparent to the pilot, and that, to a first level, the effects on pilot *ratings* are similar.

Figure 1 shows the relevant data from Refs. 47 and 26 on a plot of Bandwidth frequency versus Phase Delay. Figure 1a is for Category A MTEs, and Figure 1b is for precision offset landing (new Category D). For the reasons discussed above, there are numerous HQRs worse than 3 in the propose Level 1 regions on both figures. This greatly complicates the ability to define a clear Level 1 limit. The reasoning used here was as follows:

- Cases with ratings of 4 or worse that are located near cases with good ratings may have other factors, primarily incorrect control gain;
- Cases with an average rating of better than 3.5 should *never* lie in a region of poor Bandwidth or high Phase Delay. It is possible to have bad ratings in a good region, but not to have good ratings in a bad region.

The Level 1 Phase Delay limits drawn on Figure 1 encompass all configurations with overall Level 1 average HQRs. There is no clear interrelationship between Bandwidth and Phase Delay, in part due to a lack of data, so the limits are drawn as straight lines. Because of this shortage of data, the Level 2 limits must be considered tentative at this time. There are not enough low-Bandwidth points to define limits on Bandwidth frequency with any certainty.

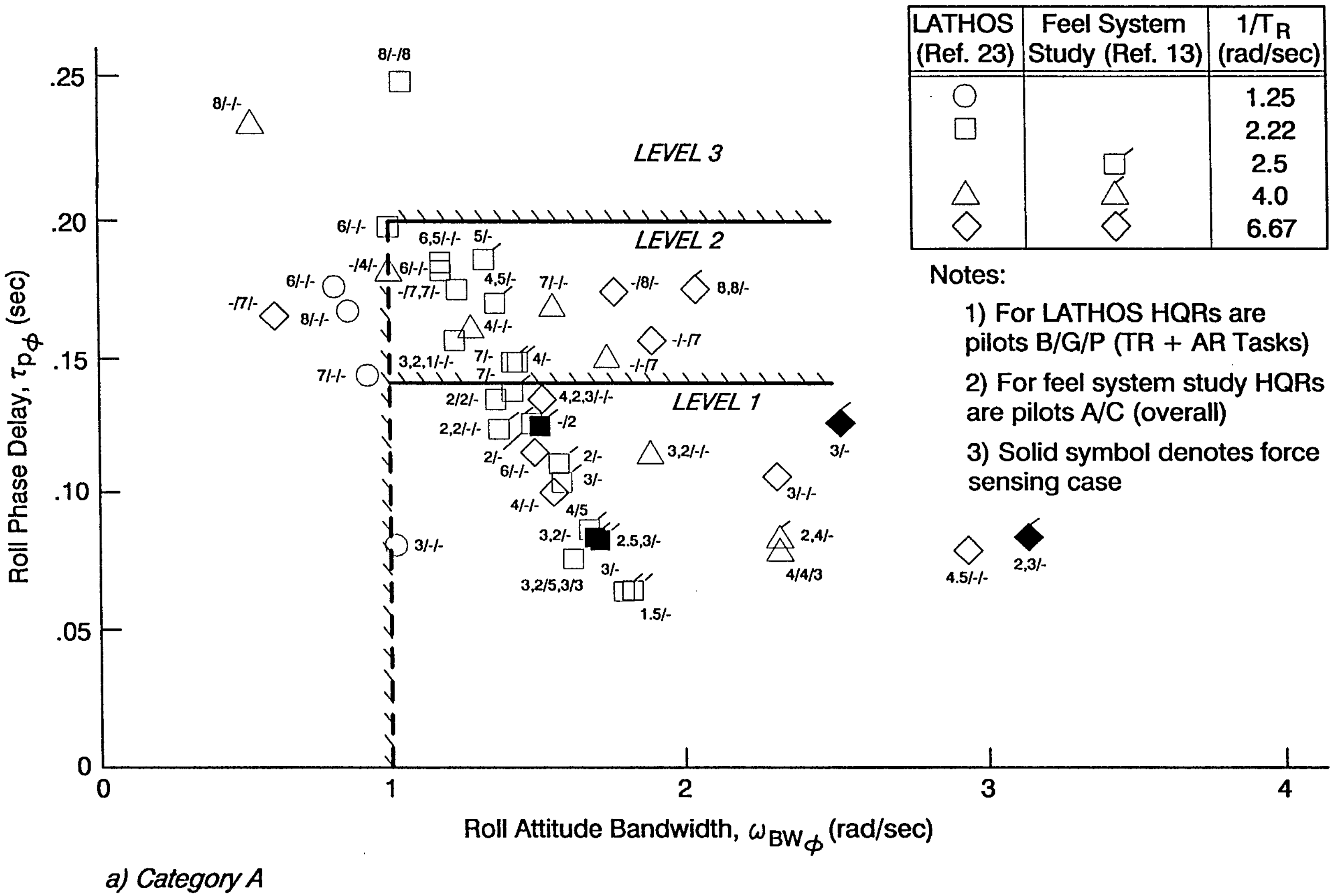
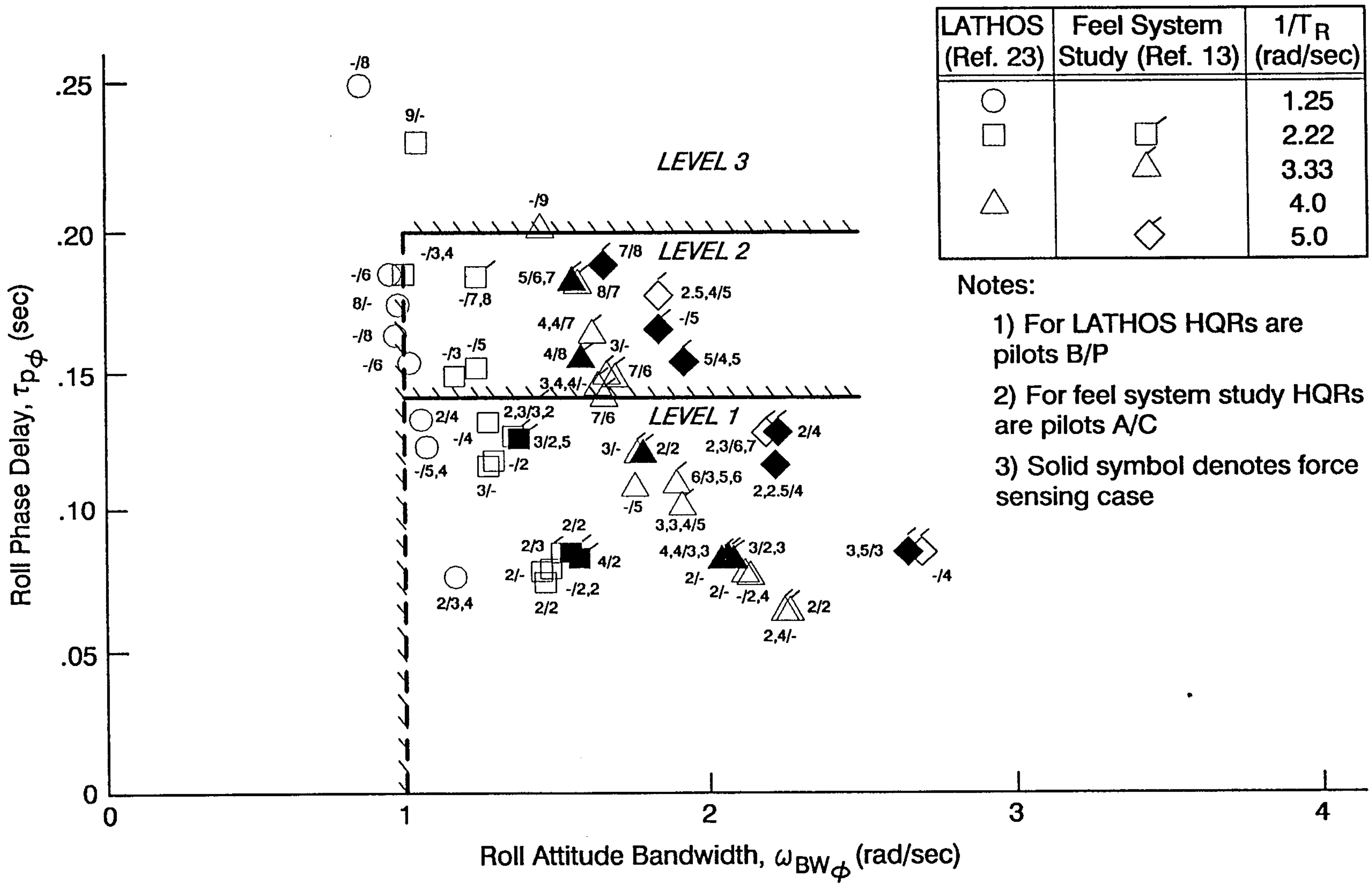


Figure 1 (4.5.1.1). Roll Bandwidth Data (Ratings are for Best Sensitivity)



b) Category C (Precision Offset Landing)

Figure 1 (4.5.1.1). Roll Bandwidth Data (Ratings are for Best Sensitivity) (concluded)

Interestingly, the Phase Delay limits are identical for Categories A (Figure 1a) and C (Figure 1b). This suggests that the response demands are not a strong function of task or flight condition. Remember, however, that the widest variation in Figure 1 is in Phase Delay, not Bandwidth, and task effects are more likely to show up in the Bandwidth requirements.

4.5.1.5 Roll time delay

1. RECOMMENDED REQUIREMENT

4.5.1.5 Roll time delay. The value of the equivalent time delay, τ_{e_p}, *including the cockpit control feel system*, shall be no greater than *the limits specified in Table 1.*

TABLE 1(4.5.1.5). LIMITS ON EQUIVALENT TIME DELAY
(Including Feel System)

LEVEL	ALLOWABLE DELAY (sec)	
	CLASS I, II-L, III	CLASS II-C, IV
1	0.20	0.20
2	0.24	0.24
3	0.33	0.33

2. RATIONALE FOR REQUIREMENT

This requirement is intended to insure that the effective time delay due to filters, lags, digital delays, feel systems, etc., does not degrade handling qualities.

3. REQUIREMENT GUIDANCE

Application of this paragraph is most straightforward if an equivalent-systems match to the higher-order aircraft response of roll rate to control force, p/F_{as} is performed. Equivalent time delay is the delay value resulting from such an equivalent-systems match. As is demonstrated in this report, it is most appropriate to include the dynamic effects of the cockpit control feel system in the higher-order response. Additional proof is shown in the Supporting Data discussion.

The time delay limits specified in Table 1 are relaxed from those of MIL-STD-1797A, especially for Levels 1 and 3. Part of this relaxation results from including the feel system here, where it was to be

excluded in MIL-STD-1797A. There is insufficient data for transports to determine reasonable limits at this time, so the values determined for Class IV aircraft are simply restated for all Classes.

4. SUPPORTING DATA

As with all of the revised or new roll requirements in this report, the basic supporting data come from two Calspan NT-33A flight experiments, LATHOS (Ref. 47) and the feel system study (Ref. 26). These data are discussed in great detail in the Supporting Data discussion for 4.5.1.1, and in Ref. 19, and will not be described again here. The data used for this paragraph are the same as those for 4.5.1.1, with one exception: all configurations with a roll mode time constant (either actual or equivalent) longer than 0.8 sec have been eliminated from this analysis. There is evidence that such low roll damping degrades handling qualities no matter what the value of time delay.

Because there is some controversy over whether or not to account for the feel system as a part of the total aircraft, the analysis was performed both ways. By excluding the feel system the requirements of MIL-STD-1797A are met; including it meets the recommendations of this report.

Figure 1 shows plots of average HQR versus equivalent time delay with the feel system excluded. The MIL-STD-1797A limits are sketched on the plots. Recognizing that there is an unusually large amount of rating variations as a result of the large number of experimental variables (discussed in Supporting Data for 4.5.1.1), we should not be too surprised to find Level 2 ratings in the Level 1 region or Level 3 ratings in the Level 2 region. If the limits are valid, however, we should *not* find Level 1 ratings in the Level 2 region or Level 2 ratings in the Level 3 region. Unfortunately, in Figure 1 we see both.

First, the 1979A Level 1 limit of 0.10 sec appears to be too stringent, as Level 1 ratings are obtained for time delays as high as almost 0.14 sec. Second, the Level 2 limit of 0.20 sec may be too lenient, because the last Level 2 ratings are at a time delay of about 0.18 sec. Third, there are many Level 2 and 3 configurations solidly in the Level 1 region for the landing data (Figure 1b). These are all from the feel system study of Ref. 26: they are the cases for which feel system frequency was varied. By excluding the feel system we have missed this critical degradation in handling qualities.

Figure 2 repeats the data with the feel system included. The time delay limits sketched here are based on the data presented. We see that much of the apparent data scatter of Figure 1 — primarily that from the feel system study — is now gone. In fact, the *trends* of degrading pilot opinion with time delay are much better, although the *Levels* are quite different. Based on Figure 2, a reasonable Level 1 time

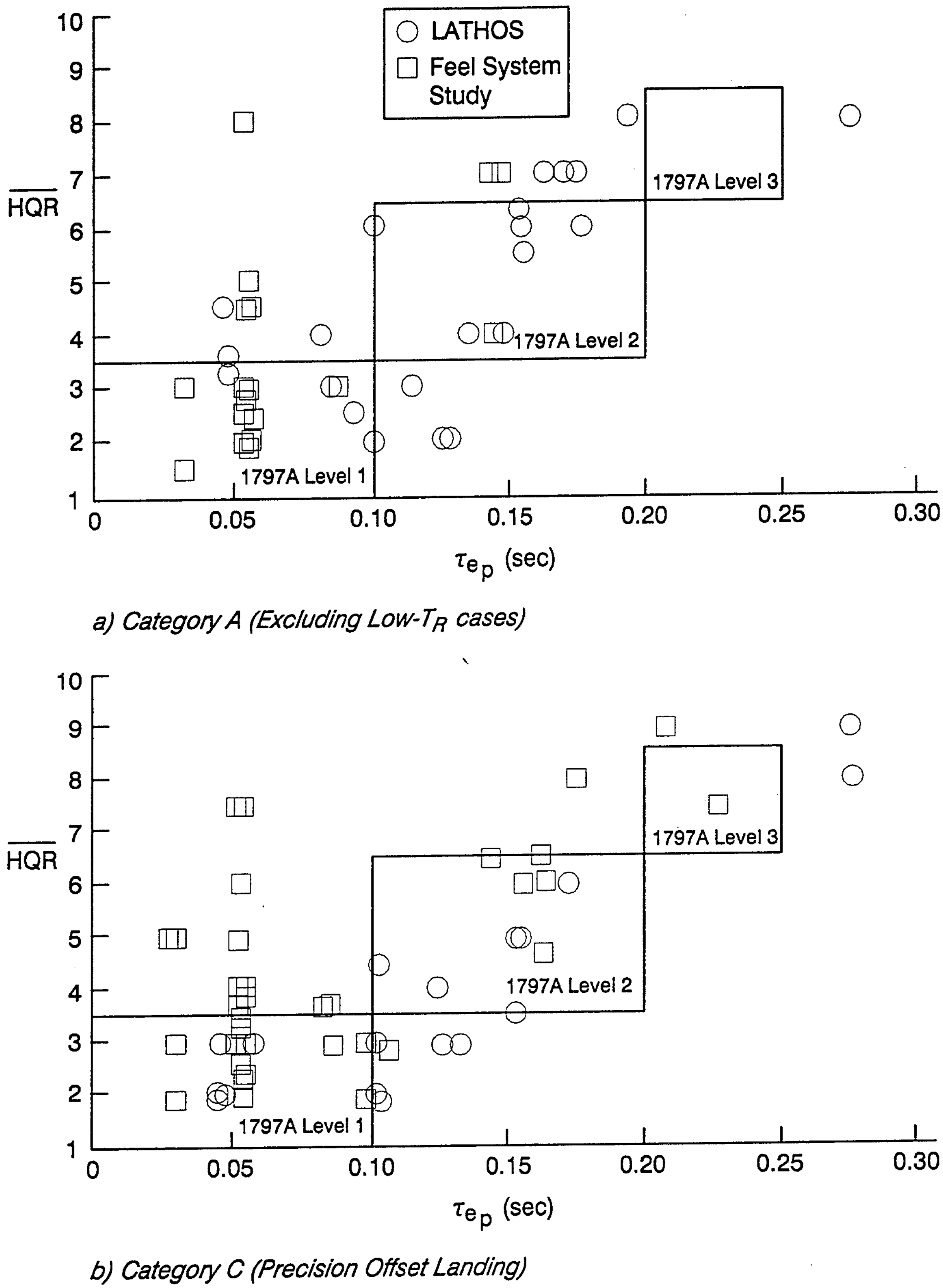
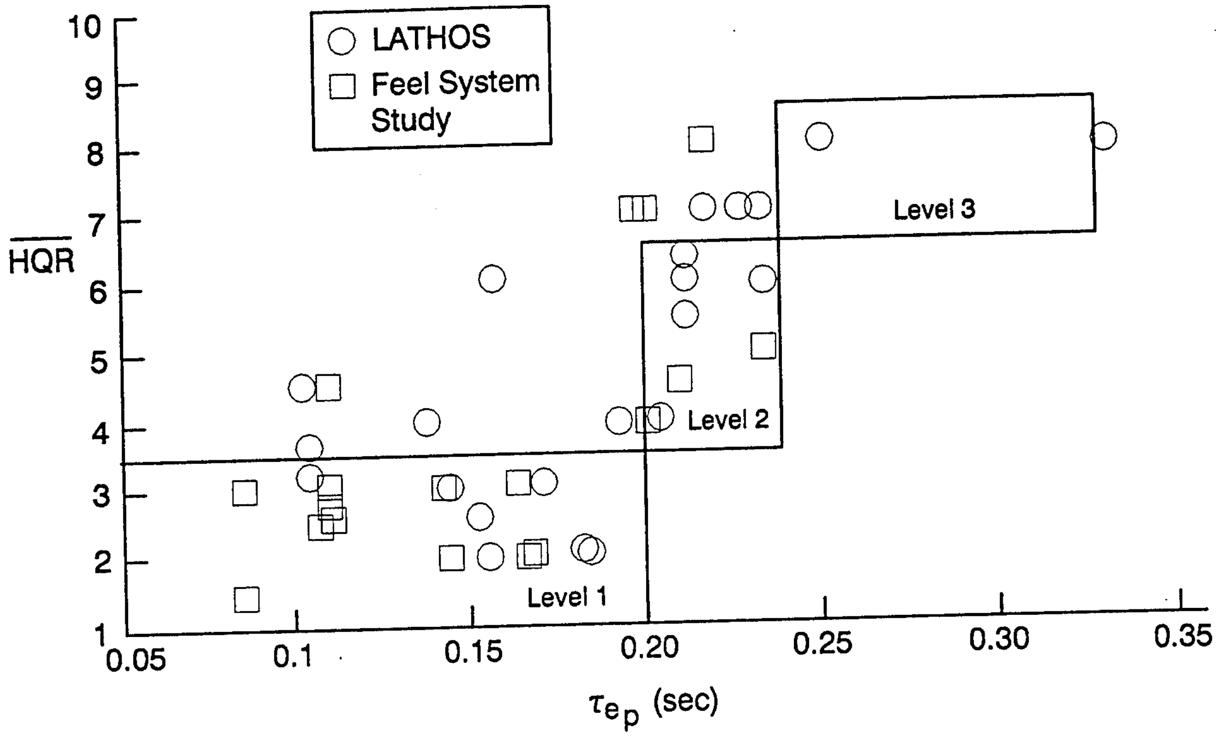
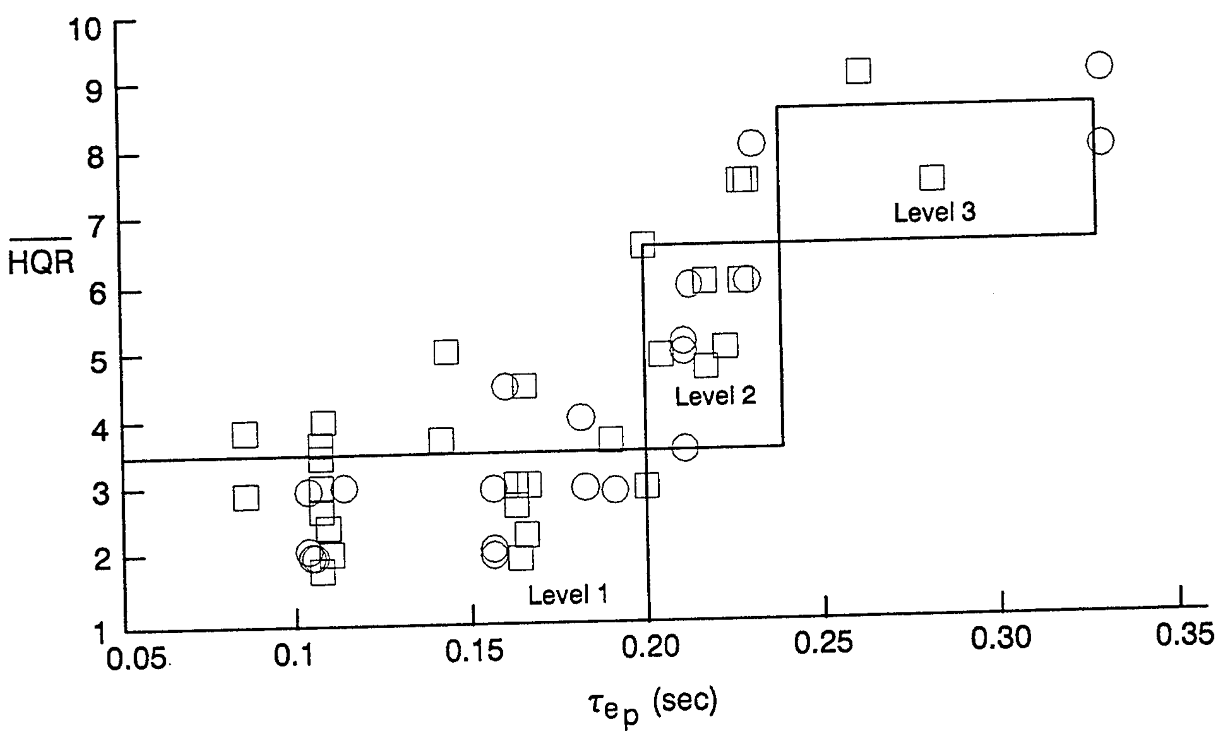


Figure 1(4.5.1.5). Equivalent Time Delay *vs.* HQR for Two Roll Experiments
(Feel System Excluded per MIL-STD-1797A)



a) Category A (Excluding Low-T_R cases)



b) Category C (Precision Offset Landing)

Figure 2(4.5.1.5). Equivalent Time Delay *vs.* HQR for Two Roll Experiments (Feel System Included in All Cases)

delay limit is roughly 0.20 sec (no Level 1 ratings occur for time delays above this value), Level 2 is at about 0.24 sec, and Level 3 is set at about 0.33 sec — based entirely on the fact that this is the highest value of equivalent delay tested.

These new limits are listed in Table 1. For a nominal feel system, contributing an incremental equivalent delay of around 0.06 sec, all of the limits represent a relaxation from MIL-STD-1797A. The reasons for a relatively small Level 2 region are not known at this time; it is entirely possible that the few Level 3 cases with high time delays also had some other characteristic that contributed to the degraded ratings — that is, the lack of Level 2 ratings above 0.24 sec in Figure 2 may be due more to the design of the experiment and a lack of configurations with higher delays than to the fact that such amounts of time delay are indeed Level 3. The proposed Level 2 limit is thus potentially conservative.

5. REQUIREMENT LESSONS LEARNED

Unfortunately, the lessons learned for roll handling qualities in general are not nearly as great as those for pitch. A search for lessons learned for this requirement was considered beyond the scope of the contract.

4.5.1.6 Moderate-amplitude roll response (attitude quickness) for aggressive Mission Task Elements

1. RECOMMENDED REQUIREMENT

4.5.1.6 Moderate-amplitude roll response (attitude quickness) for aggressive Mission Task Elements. *The ratio of peak roll rate to peak change in roll attitude, $p_{pk}/\Delta\phi_{pk}$ shall meet the limits specified in Figure 1. The required attitude changes shall be made as rapidly as possible from one steady attitude to another without significant reversals in the sign of the cockpit control input relative to the trim position. The attitude changes required for compliance with this requirement shall vary from 10 deg to the limit of the Operational Flight Envelope or 90 deg, whichever is less. Parameters required for Figure 1 were defined in Figure 1b(4.2.1.3).*

2. REQUIREMENT RATIONALE

The parameter $p_{pk}/\Delta\phi_{pk}$ is related to Bandwidth, so this requirement effectively allows decreasing roll attitude Bandwidth with increasingly large inputs. As the amplitude increases beyond small values, this interpretation becomes less appropriate, and the boundaries are better interpreted as a measure of agility. Failure to meet the limits often results from inadequate rate limits on the roll control surface actuator that can lead to pilot-induced oscillations. The requirement is intended to apply above the attitude changes normally associated with fine tracking.

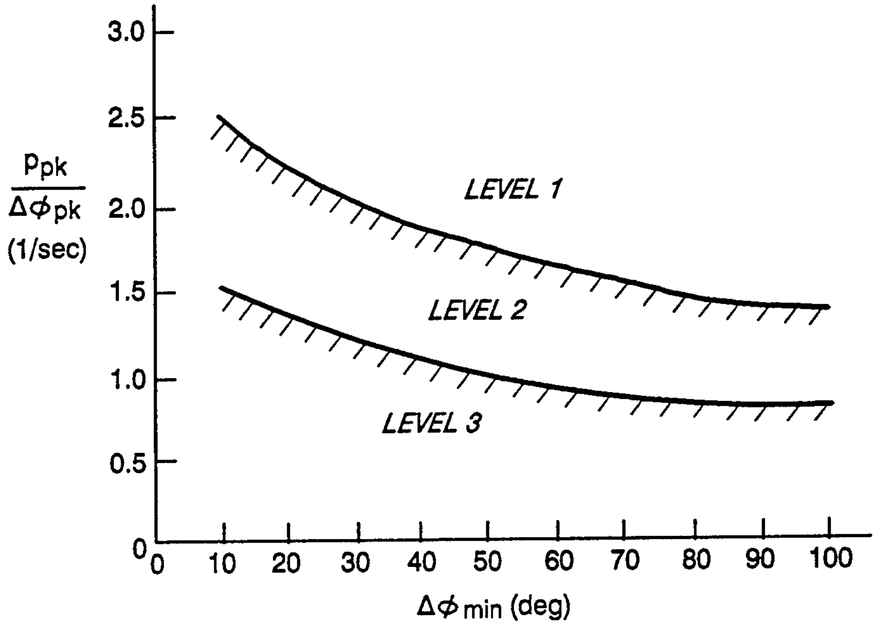


Figure 1(4.5.1.6). Requirements on Moderate-Amplitude Roll Response (Attitude Quickness) for Aggressive Maneuvering

3. REQUIREMENT GUIDANCE

Background for this requirement, and its pitch counterpart (4.2.1.3), can be found in the helicopter roll control study of Ref. 38. The details of the requirement have undergone constant review and improvement for the helicopter specification (Ref. 5) as experience with its application has been gained. Since the ability to roll is not unique to either type of aircraft, the basic structure of this requirement is equally appropriate for both helicopters and conventional airplanes. The specific limits of Figure 1 are based on the results of the simulation performed for this contract, as documented in Appendix A and summarized below.

In the flight and ground simulation programs of Ref. 38, a number of discrete lateral maneuvering tasks were devised, from which "maneuvering performance" diagrams were constructed. The technique for constructing such plots is sketched in Figure 2. For a maneuver that requires discrete control inputs (inputs that closely resemble square waves, Figure 3) the crossplot of peak roll rate, p_{pk}, versus bank angle change, $\Delta\phi$, for the entire maneuver represents a "task signature" (Figure 4) related to the pilot's demands on the vehicle. For example, a high ratio of $p_{pk}/\Delta\phi$ means that the pilot requires high agility in the roll axis, while a low ratio (for the same bank angle change) indicates a correspondingly low roll performance demand.

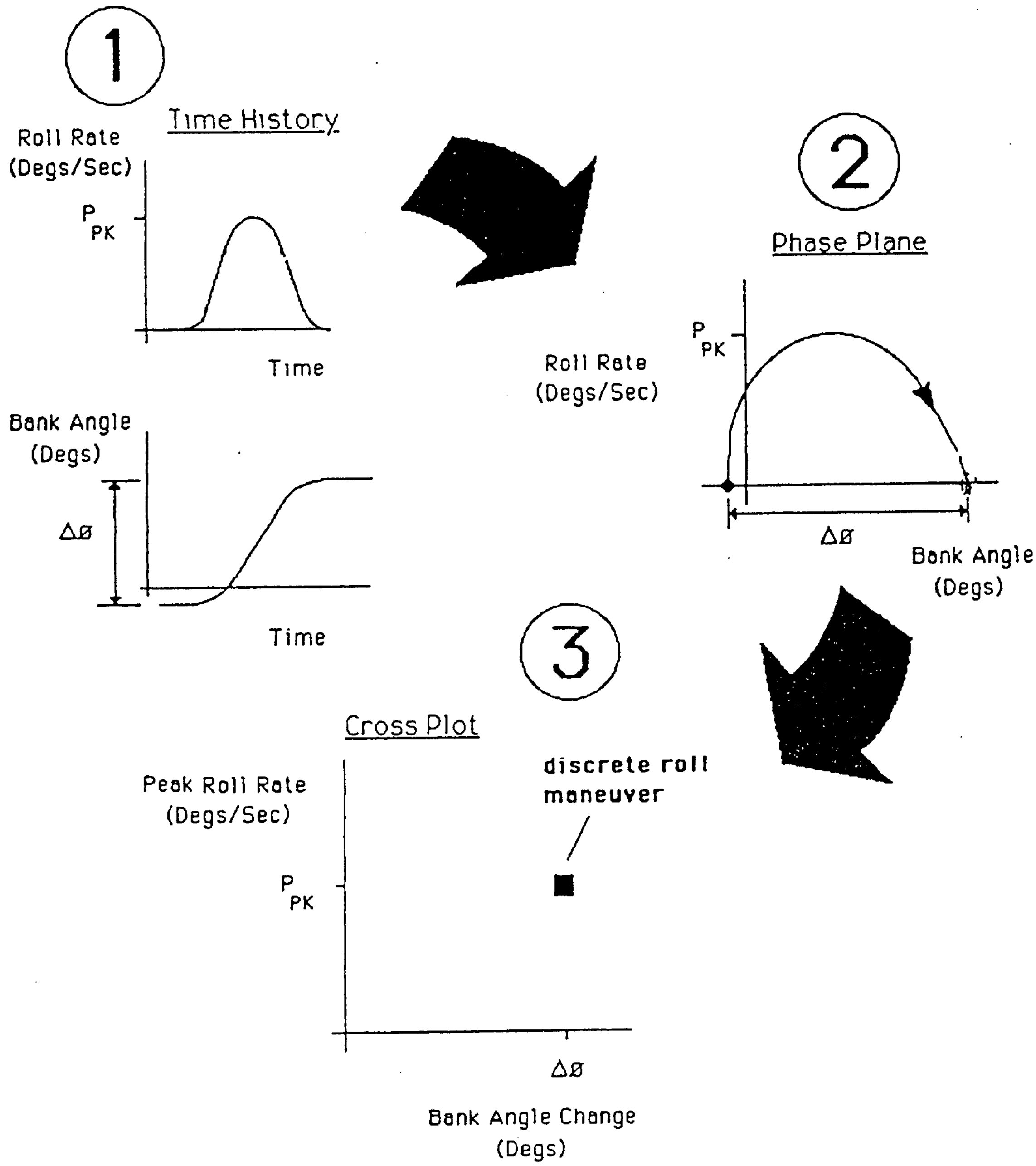


Figure 2(4.5.1.6). Analysis Technique for Discrete Roll Maneuver Data (from Ref. 7)

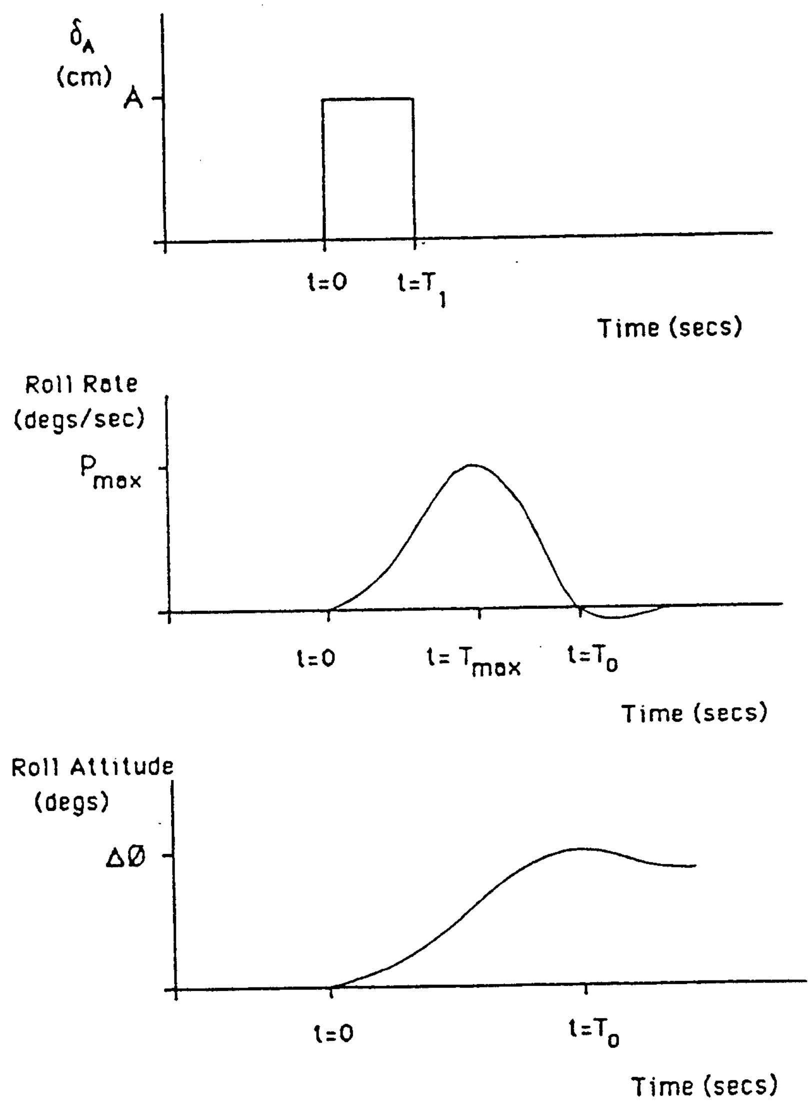


Figure 3(4.5.1.6). Characteristics of Square Wave Input Response for a Rate Response-Type
(from Ref. 7)

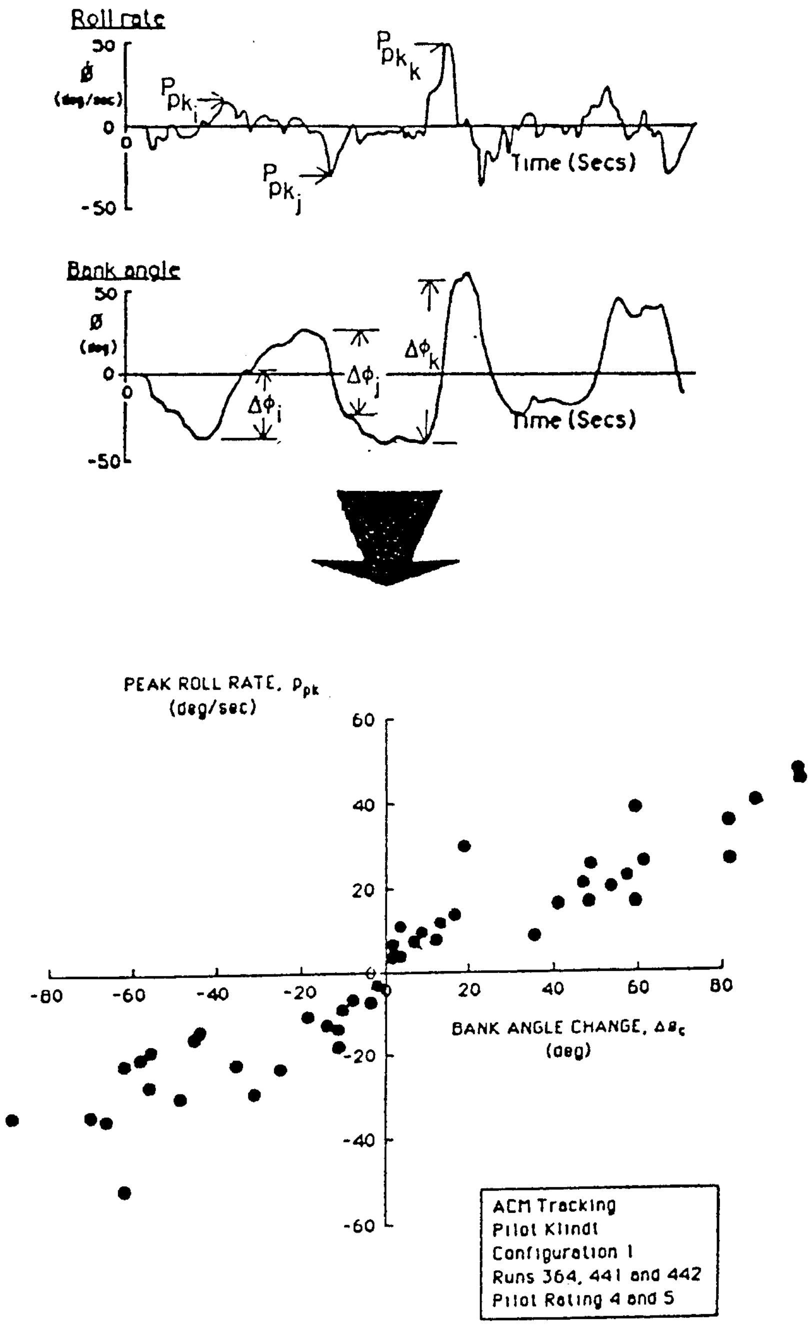


Figure 4(4.5.1.6). Definition of the "Task Signature" from Discrete Maneuver Time Histories (from Ref. 7)

For an ideal airplane whose roll response is dictated entirely by the roll mode time constant, T_R, in the absence of any time delays the Bandwidth frequency, ω_{BW_ϕ}, is identically equal to $1/T_R$. In this case the ratio $p_{pk}/\Delta\phi_{pk}$ is also equal to $1/T_R$. When any limiting in the control system is reached (either rate or position limits of the surface or cockpit controller), this relationship is no longer true and attitude quickness decreases. The requirement on attitude quickness in Figure 1 is therefore a relaxation in the demands for agility as bank angle increases, reflecting both the requirements of the pilot and the realities of the airplane. More information on the attitude quickness parameter may be obtained from Ref. 48.

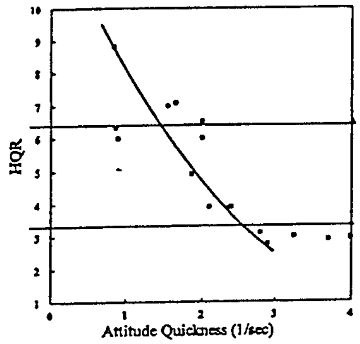
Ideally, the maneuver to show compliance with this requirement would have the characteristics shown in Figures 2 and 3. As a practical matter, however, the "steady" attitude achieved may be difficult to define due to overshoots and drifting that may be imperceptible to the pilot. Therefore, the attitude change between initiation of the maneuver and the *first peak* is taken as the denominator of $p_{pk}/\Delta\phi$.. The required change from "one steady attitude to another" is taken as the first minimum following the first peak of the response, $\Delta\phi_{min}$. If there is no attitude overshoot, the peak and steady attitude changes are identical. These definitions penalize large attitude overshoots; large attitude overshoots are not consistent with the intention of the requirement, where a crisp attitude change without overshoot is the desired goal.

4. SUPPORTING DATA

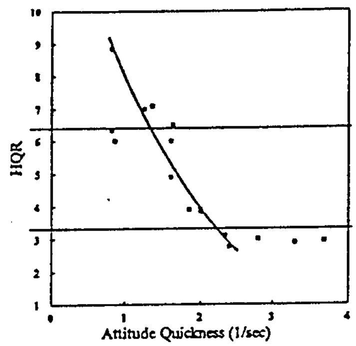
A piloted simulation was performed in support of this contract to develop the requirements on attitude quickness. Details of the simulation are given in Appendix A.

The simulation focused primarily on roll attitude quickness requirements with a large matrix of variations in roll response dynamics. For roll, the only response type evaluated was a basic rate-augmented system. Variations in roll attitude quickness were made by a combination of variations in the basic roll mode time constant (T_R of 0.2, 0.333, and 1 sec) and rate limits on the simulated aileron actuator. The dynamics of the actuator were set very high (second-order filter with a natural frequency of 75 rad/sec) to minimize the effects of the basic actuator dynamics on pilot ratings. The pitch dynamics were not changed for the roll evaluations. Task details are given in Appendix A; five pilots evaluated roll actuator rate limits of infinity and 80, 40, and 20 rad/sec.

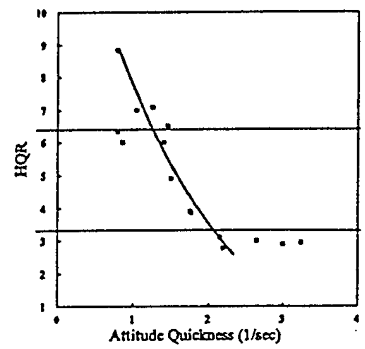
Construction of the limit drawn in Figure 1 followed the format developed in Ref. 39. Attitude quickness was calculated for bank angle changes from 10 to 100 deg in 10-deg increments, using ideal inputs and models of the test configurations. Average Cooper-Harper Handling Qualities Ratings were crossplotted against the ideal attitude quickness for each configuration at each bank angle change, as shown in Figure 5. Values of attitude quickness were read off of each plot where the faired line crossed



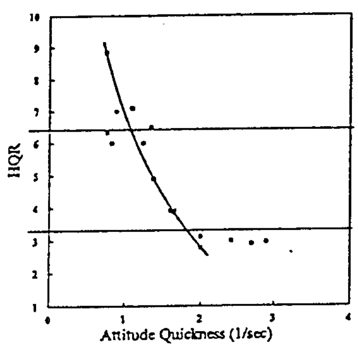
a) Bank angle change = 10 deg



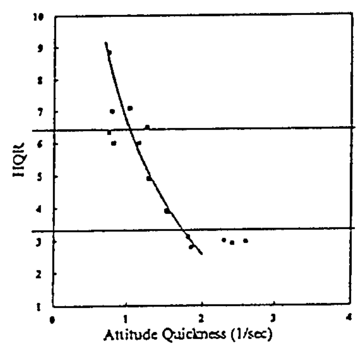
b) Bank angle change = 20 deg



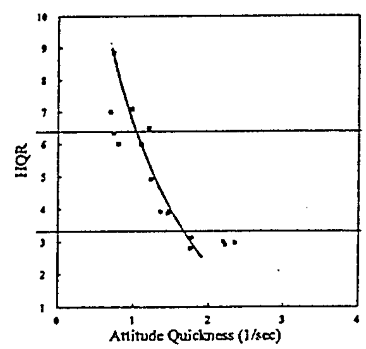
c) Bank angle change = 30 deg



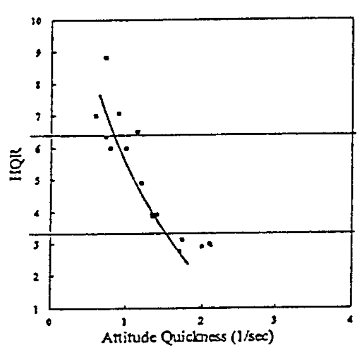
d) Bank angle change = 40 deg



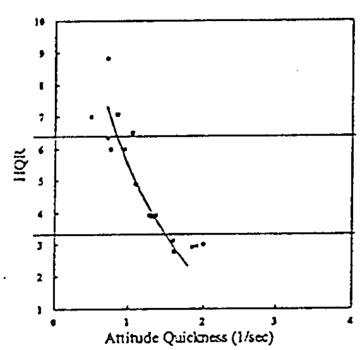
e) Bank angle change = 50 deg



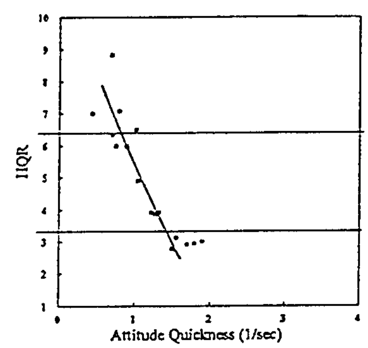
f) Bank angle change = 60 deg



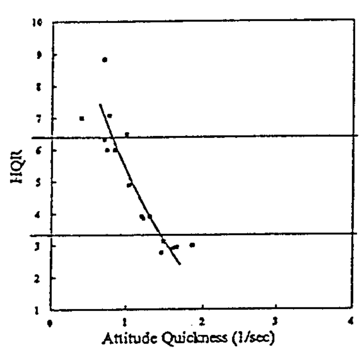
g) Bank angle change = 70 deg



h) Bank angle change = 80 deg



i) Bank angle change = 90 deg



j) Bank angle change = 100 deg

Figure 5(4.5.1.6). Average Handling Qualities Rating *vs.* Ideal Attitude Quickness in Roll for Variation Cases from Simulation (Appendix A)

the HQR = 3-½ and 6-½ lines, and these values were transferred to a crossplot of attitude quickness and bank angle change, resulting in the boundaries in Figure 1.

These requirements may be conservative. For example, since the limits in Figure 1 are close to required Bandwidth (which is approximately $1/T_R$ for the simple roll models used in the simulation) at low bank angle changes, the results suggest that a minimum Bandwidth (or $1/T_R$) of 2.5 to 3 rad/sec is required for Level 1. This is well above the allowable Level 1 value of $1/T_R$ = 1 rad/sec from 4.5.1.1 of MIL-STD-1797A. In the simulation documented in Appendix A, the best configurations evaluated ($1/T_R$ = 5 rad/sec, no actuator rate limiting or rate limit at 80 deg/sec) received average HQRs of around 3. When $1/T_R$ = 3 rad/sec, the best configuration evaluated (with an actuator rate limit of 80 deg/sec) received an average HQR of 3.9, or Level 2. Hence the minimum acceptable value of $1/T_R$ for Level 1 was probably somewhat higher than 3 rad/sec, well beyond the MIL-STD-1797A limit. When $1/T_R$ was reduced to 1 rad/sec (resulting in an effective roll mode inverse time constant of less than 1 rad/sec due to simulation delays), the 80-deg/sec rate-limited case was rated a 6.0.

Whether this requirement for considerably higher roll damping is a consequence of the simulation environment, the task, or both cannot be resolved without further experimentation, preferably flight testing. Nevertheless, it must be recognized that until further testing is done the Figure 1 limits are conservative, and they should be applied only for aggressive maneuvering mission tasks.

5. REQUIREMENT LESSONS LEARNED

Experience with this requirement in the helicopter specification has revealed several important lessons. The most important is to avoid confusion over how to perform flight test inputs. In the Army's assessment of the attitude quickness requirement with an AH-64A Apache (Ref. 49), two types of input techniques were attempted. The first involved "boxcar" inputs, modified in both amplitude and duration to attain specified attitude changes. The second technique used "spike" inputs, forcing the input duration to be an absolute minimum and adjusting only amplitude. This second technique resulted in larger values of the attitude quickness parameter and is representative of what is being tested for. The nature of the parameter is that larger values better represent the capability of the rotorcraft as long as control reversals are not used. According to Ref. 49, "The spike input technique (minimum input duration, and no target attitude change) yielded significantly better results (more desirable level) than the 'boxcar' inputs (attaining target attitude change as rapidly as possible)." The "spike" input resulted in increased attitude quickness, and better demonstrates the capability of the aircraft.

It is important to emphasize that the maneuver for obtaining attitude quickness parameters is *open loop*. The pilot should experiment with the type of open loop control inputs that cause the aircraft to change attitude as quickly as possible, and cover the desired range of amplitudes.

4.5.2 Pilot-in-the-loop roll oscillations

1. STATEMENT OF REQUIREMENT

4.5.2 Pilot-in-the-loop roll oscillations. There shall be no tendency for sustained or uncontrollable roll oscillations resulting from efforts of the pilot to control the aircraft. *For Categories A and D, the roll attitude Phase Delay parameter, τ_{p_ϕ}, including the effects of the cockpit control feel system, shall be less than 0.17 sec.*

2. REQUIREMENT RATIONALE

This is the roll counterpart to 4.2.2, pilot-in-the-loop pitch oscillations. Prevention of roll PIOs basically involves good Dutch roll dynamics, adequate roll damping, and correct roll control sensitivity. Because all of these elements are explicitly addressed by other requirements in MIL-STD-1797A — and because it is not possible at this time to set specific limits on any of them to prevent PIOs — this paragraph addresses only Phase Delay. Meeting the other lateral and directional requirements should prevent PIOs; the requirement proposed here is only a further check, especially if the roll Phase Delay requirements are not met.

3. REQUIREMENT GUIDANCE

Unlike pitch, the number of possible contributors to roll PIO is relatively small. Unfortunately, the data base for specifying limits on these contributors to prevent PIOs is even smaller. On the basis of recent flight experiments, as long as the Dutch roll dynamics are well-behaved, the only major elements in the occurrence of roll PIOs are Phase Delay and control sensitivity. These experiments and their data are discussed in Supporting Data below.

There is clearly much more work to be done to identify the causes and cures for roll PIOs.

4. SUPPORTING DATA

The primary supporting data for this paragraph come from two Calspan-conducted flight research studies using the variable-stability NT-33A. The studies, referred to here as LATHOS (Ref. 47) and the

feel system study (Ref. 26), are described in some detail in the Supporting Data discussions for 4.5.1.1. The most important points to bear in mind here are that these studies looked only at the effects of roll damping, added time delays and lags, and control sensitivity on handling qualities. There were very few variations in Dutch roll dynamics; the roll mode variations did not include very low values of roll damping; and PIO ratings were not gathered in either experiment. Thus we can only observe the effects of changes in roll Phase Delay and control sensitivity on HQRs, and from these infer the potential for PIO.

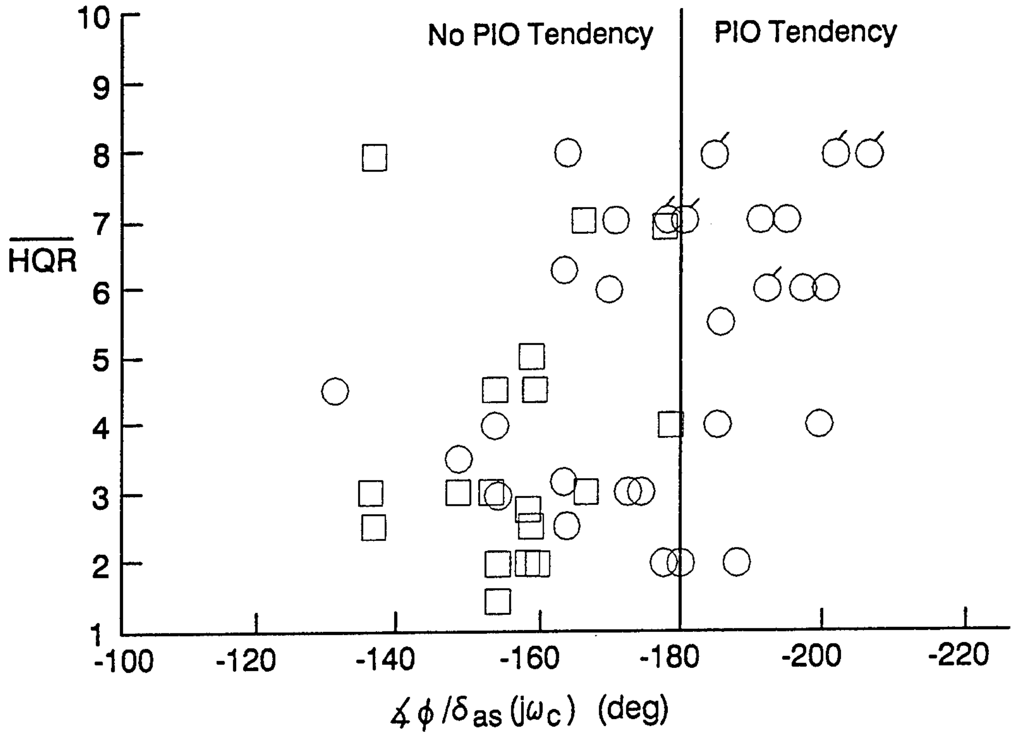
As explained in Supporting Data for 4.5.1.1, the data of Refs. 47 and 26 must be carefully screened before using any of it. Because control sensitivity (described in both references in terms of roll rate per lb, deg/sec/lb) was a part of the experimental matrices, it is sometime difficult to determine if a poor HQR is due to sensitivity, roll damping, or time delay. In addition, the number of different values of control sensitivity tested was small, so there is no assurance that the "best" value was ever tested with a given set of dynamics. This complication does not invalidate the data, but it does make their interpretation much more difficult. As with the analysis in 4.5.1.1, only a subset of the data from either experiment will be used here. This subset is the same as that used for 4.5.1.1.

a. Proposed Criteria for PIO Prevention

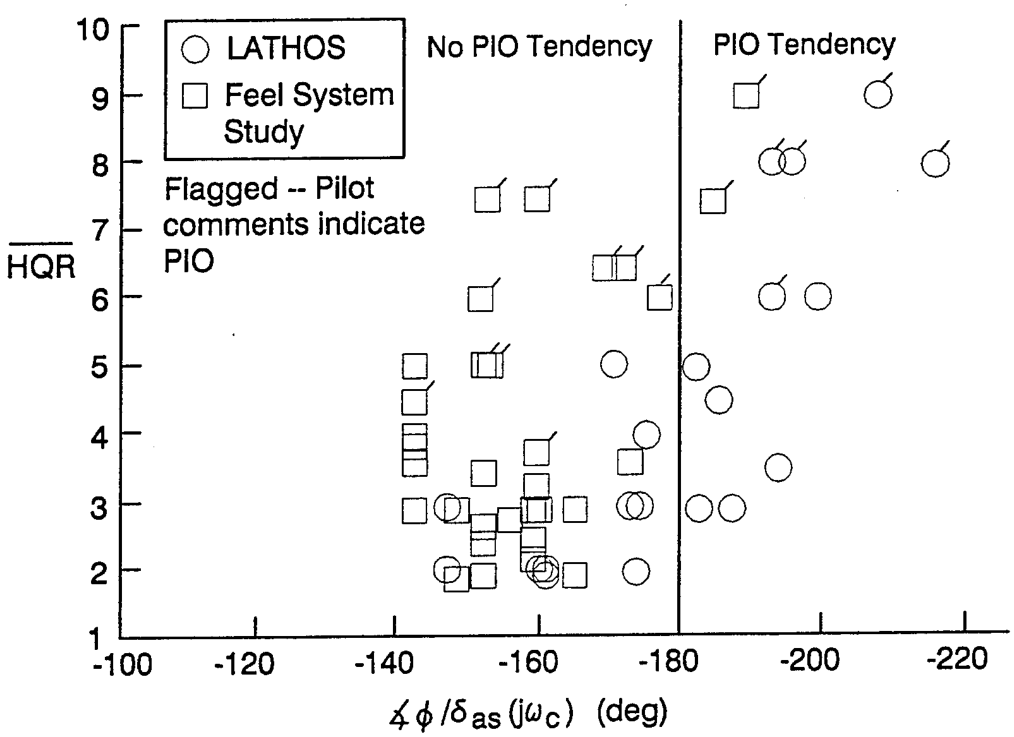
At this writing, there is a plan to include a version of the Smith-Geddes PIO criteria (see discussion for 4.2.2 and Appendix E) in the next revision to MIL-STD-1797A. On this basis, the first step was a review of the effectiveness of these criteria for predicting PIOs using the data of Refs. 47 and 26.

Because there is also some disagreement about how to deal with the dynamics of the cockpit control feel system (i.e., exclude them altogether, include them only when position command sensing is used, or include them at all times), the approach here has been to perform the analysis with the feel system both excluded and included.

Figures 1 and 2 show the relevant pilot rating data from Refs. 47 and 26 plotted against roll attitude phase angle at the criterion frequency. In Figure 1, with the feel system excluded, there is considerable scatter in the data. In fact there is only a very slight trend seen in these plots. When the feel system is



a) Category A



b) Category C

Figure 1(4.5.2). Comparison of Handling Qualities Ratings from Two Roll Experiments with Smith-Geddes PIO Criteria (Feel System Excluded)

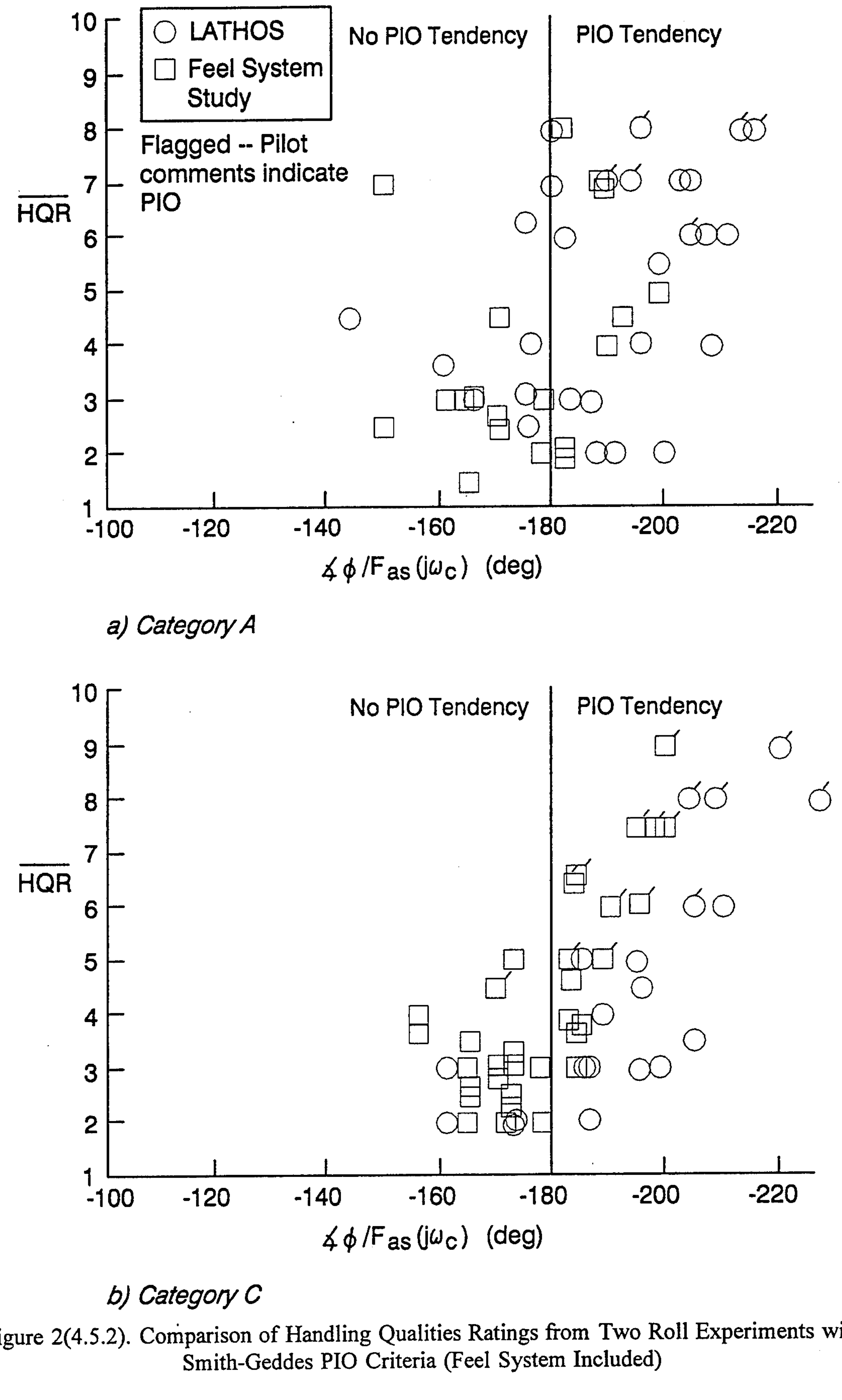


Figure 2(4.5.2). Comparison of Handling Qualities Ratings from Two Roll Experiments with Smith-Geddes PIO Criteria (Feel System Included)

included, Figure 2, the trend is stronger, though there is still scatter. Based on these figures, it is clear that

- The correlation with HQR is better if the feel system is included at all times;
- There is still a large amount of variation in ratings at any one phase angle, especially for the Category A ratings of Figure 2a, although some of this variation may be attributed to the effects of other experimental factors, such as control sensitivity;
- With the feel system excluded or included, a limit on phase angle at the criterion frequency of -180 degrees results in many good ratings on the bad side. Including the feel system results in a relatively strong trend for landing (Figure 2b), but also reflects the conservatism of these criteria found for pitch data as well (Appendix E and paragraph 4.2.2).

Because PIO ratings were not obtained, it is difficult to determine if PIO tendency was a strong factor in the pilots' ratings. Some measure of the occurrence of PIOs can be made by reviewing published pilot comments and searching for specific mention of PIOs. In both experiments the pilots were asked specifically to comment on any PIO tendency. Unfortunately, positive comments here usually reflect the *existence* of a PIO, as opposed to a *tendency* for PIO. It is always possible that some of the configurations for which there are no comments on PIO tendency would still have received poor PIO ratings if such ratings had been taken. Still, it is reasonable to expect that any PIO requirement will successfully capture most of the cases for which PIOs were reported.

In Figures 1 and 2 those cases for which the pilots explicitly reported a tendency for, or an actual, PIO are indicated by flagged symbols. (Remember that some of these PIOs may be due more to control sensitivity, which is not addressed by the Smith-Geddes criteria. It is shown below that this may have been the case.) Most comments about PIO occurred during the landing tests, and more occurred in the feel system study of Ref. 26 than in the LATHOS study of Ref. 47. As Figure 1b indicates, with the feel system ignored it is possible to get comments about PIOs for any value of phase angle. With the feel system included, as in Figure 2b, almost all PIO cases are to the right of the -180 degree line. Unfortunately, so are about half of the *non*-PIO cases. Thus these criteria are not very discerning of the potential for PIOs.

b. Alternative Requirements Based on Phase Delay

In the discussions for 4.2.2, it was found that pitch attitude Phase Delay was a prime measure of the potential for PIOs. Since the two roll experiments focused primarily on roll damping, control sensitivity, and delays and lags, it seems logical that this would be the case here as well. Because roll Bandwidth

does not appear to be a strong factor in the ratings from these experiments (see 4.5.1.1), only control sensitivity and Phase Delay need to be considered.

Figure 3 is a plot of HQR versus Phase Delay for the relevant data. Since there is ample evidence presented elsewhere in this report that the feel system should always be accounted for, the dynamics of the feel system were included for these data.

As with the plots in Figure 2, there is scatter in the data, especially for Category A (Figure 3a). Unlike Figure 2, however, the majority of cases where PIO was reported are to the right in both plots. The following observations can be made from Figure 3:

- The relatively strong correlation between HQR and Phase Delay observed in the Supporting Data for 4.5.1.1 is also observed here;

- Control sensitivity appears to indeed be a factor in the pilot ratings: the lowest values (indicated in both plots by solid symbols) may have been too low for small values of Phase Delay (the ratings are generally worse), but preferred for higher values of Phase Delay (where the ratings are generally better);

- For landing (Figure 3b), all but one of the PIO cases are above the Level 1 limit of 0.14 sec;

- Between Phase Delays of about 0.14 to 0.17 sec, the only PIO cases were those with the higher roll gain, and in several of these cases the pilots specifically mentioned the excessive control sensitivity as a factor in their ratings. Hence these cases may be PIO-prone more because of control sensitivity than Phase Delay;

- Above a Phase Delay of about 0.17 sec, only three of the 12 cases did not involve PIOs. Two of the three non-PIO cases had low sensitivity, again suggesting that decreased responsiveness may have helped alleviate the potential for PIO. But of the remaining nine PIO cases, both low and high sensitivity cases are involved, further suggesting that at this point the potential for PIO is high no matter what the control gain.

On the basis of these observations it was concluded that: 1) PIO is unlikely if Phase Delay is less than 0.17 sec, as long as sensitivity is separately optimized; 2) PIO is likely if Phase Delay is above about 0.17 sec.

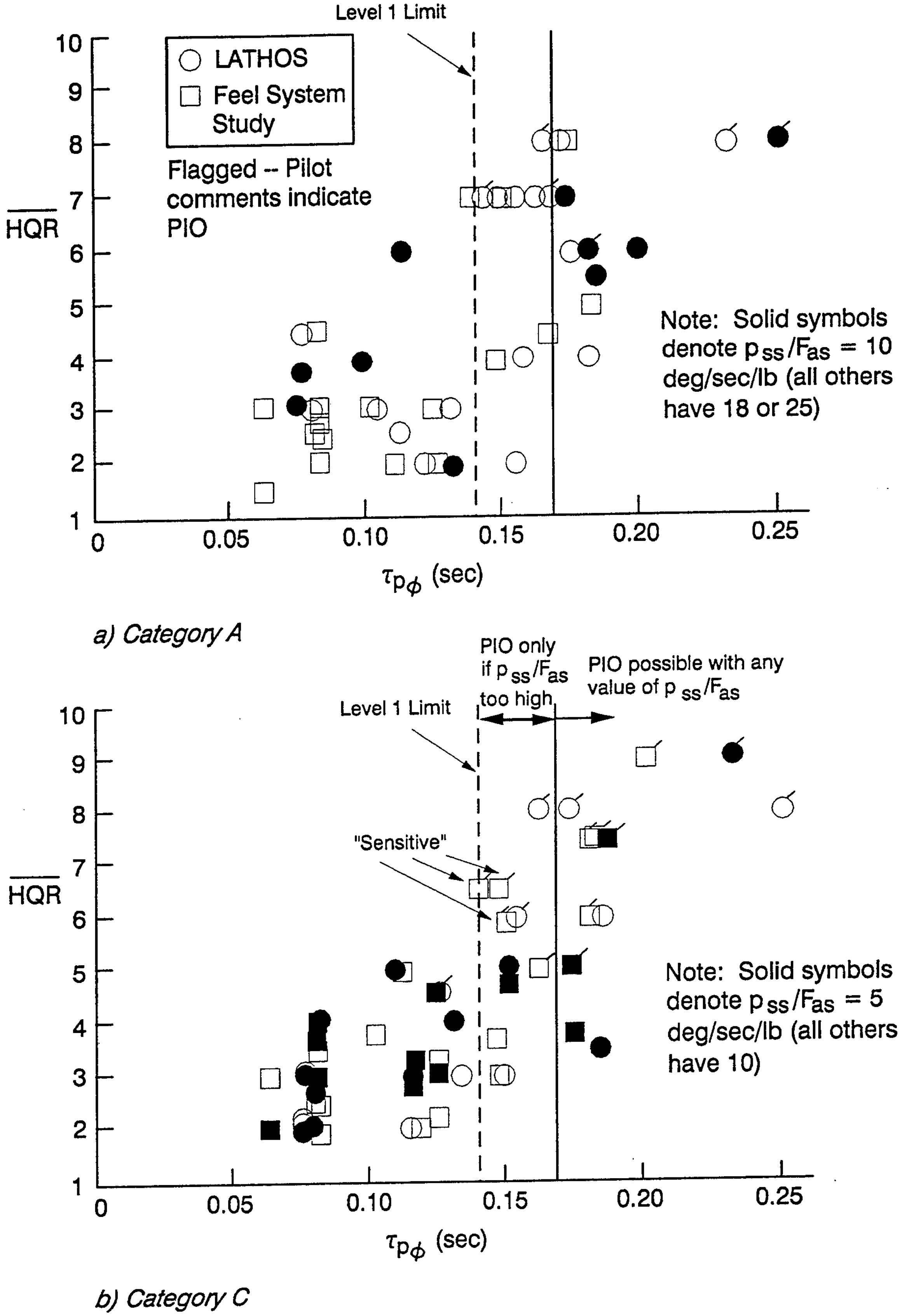


Figure 3(4.5.2). Comparison of Handling Qualities Ratings from Two Roll Experiments with Roll Attitude Phase Delay (Feel System Included)

5. REQUIREMENT LESSONS LEARNED

None.

4.5.8 Roll axis control power

4.5.8.1 Roll axis response to roll control inputs

DISCUSSION

All of the time-to-bank requirements of MIL-STD-1797A are divided by airplane Class. It should be possible (albeit with considerable labor) to redefine the requirements on the basis of Mission Task Element, and eliminate all reference to airplane size. Much of this change is simply common sense; for example, there are separate requirements on roll performance for Class IV aircraft in ground attack. Other Classes, however, sometimes perform ground attack, and in fact, some of the limits on time to roll 30 degrees for Class IV aircraft are not far from those stated for Class III aircraft in Category A. This is obviously as it should be; and a careful point-by-point comparison of all of the requirements would reveal a number of nearly overlapping requirements.

There is also some evidence that the basic requirements need revision, for example, the simulation of Ref. 50.

4.5.9 Roll axis control forces and displacements

DISCUSSION

As a part of this effort, a review of all of the roll control power and force requirements was conducted for sidestick controllers. Specific limits have been proposed for most of the control force requirements that fall under 4.5.9. A summary discussion, with the recommended changes to the military standard, is presented as Appendix D to this report.

4.6 Flying quality requirements for the yaw axis

4.6.1 Yaw axis response to yaw and side-force controllers

4.6.1.1 Dynamic lateral-directional response

DISCUSSION

The Level 1 dutch roll requirements of 4.6.1.1 are broken down in terms of airplane Class in Table XL of MIL-STD-1797A. It should be possible, through the use of the new Mission Task Element definitions, to eliminate this Class breakdown. The following are recommended changes based on a review of the supporting data for this paragraph; a more detailed analysis, and possibly one or two simulations or flight experiments, would confirm the appropriate distinctions. The supporting data lack any strong consensus for the current divisions of Table XL.

- *Flight Phase Category A (CO, GA, RR, TF, RC, FF, AS):* These are the aggressive, precision tasks of the new Category A. Therefore, the Phases stated in parentheses are not needed.

- *Flight Phase Category A (all others):* Here the requirements are divided between small (Classes I, IV) and large (Classes II, III) airplanes, with an allowance for a lower dutch roll frequency for larger airplanes. The Flight Phases covered here are generally in the new Category D, where a relatively high level of precision is still required. High dutch roll frequency and damping are thus necessary. The limits stated here are also appropriate for such Mission Task Elements as precision landing, with only the more stringent dutch roll frequency limit imposed. Thus the only difference between this set of requirements and those for Category A will be dutch roll damping.

- *Flight Phase Category B:* This set of requirements now applies to the new Category B. Note that this includes non-precision landings, previously covered by the old Category C.

- *Flight Phase Category C:* Again there is a division of requirements between airplane Classes, for both dutch roll damping and the product $\zeta_d\omega_d$. The dutch roll limits for smaller airplanes are appropriate for the new Category D, where high aggressiveness is required, but high precision is not. Low dutch roll damping will interfere with such tasks as precision pointing, but will not have a greatly adverse effect on non-precision tasks. This change would mean that the only difference in requirements between Categories C (non-precision, aggressive) and B (non-precision, non-aggressive) is the minimum value of dutch roll frequency.

If these changes are made all reference to airplane Class in Table XL can be removed.

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APPENDIX A

PILOTED SIMULATION INVESTIGATION OF PITCH AND ROLL ATTITUDE QUICKNESS REQUIREMENTS

A. INTRODUCTION

One of the tasks in this effort to upgrade and incorporate mission oriented flying qualities into MIL-STD-1797A has been the definition and resolution of critical gaps in the flying qualities database. In Phase I of this study, flying qualities requirements for moderate amplitude maneuvering were identified as one area that required further research. A criterion for assessing flying qualities during moderate amplitude maneuvering in pitch and roll was also suggested in Phase I. One of the primary tasks for Phase II of this study was the further development and verification of this criterion and its associated boundaries.

The development and verification of the moderate amplitude maneuvering criterion was accomplished through a piloted simulation experiment conducted at the Air Force Flight Dynamics Directorate research simulation facilities at Wright-Patterson Air Force Base (WPAFB) in Dayton, OH. The simulation was conducted during January-February, 1994, over a five week time period that included approximately three weeks of setup/checkout time.

The primary emphasis of the experiment was on moderate amplitude maneuvering in roll as the lateral axis as most gross acquisition maneuvers involve significant gross maneuvering in the lateral axis. Moderate amplitude maneuvering requirements in pitch and the effect of different pitch response-types on flying qualities during a simulated formation flying/aerial refueling task were also investigated. As presented in the main text of this report, HQR results from the lateral axis evaluations were used to develop flying qualities boundaries for moderate amplitude maneuvering in roll. The results of the equivalent, but more limited, evaluations in the longitudinal axis were used to develop tentative boundaries for moderate amplitude maneuvering in pitch. The results (primarily pilot comments) for the simulated formation flying/air-refueling task indicated the preferred pitch response-type for this type of precision task.

B. SIMULATOR DESCRIPTION

1. Overview

The majority of the evaluations were performed on the Mission Simulator One (MS-1) research simulator at WPAFB. A limited evaluation of the effect of motion on task performance was also conducted, using one subject pilot, on the Large Amplitude Multi-mode Aeronautical Research Simulator (LAMARS), situated at the same facility.

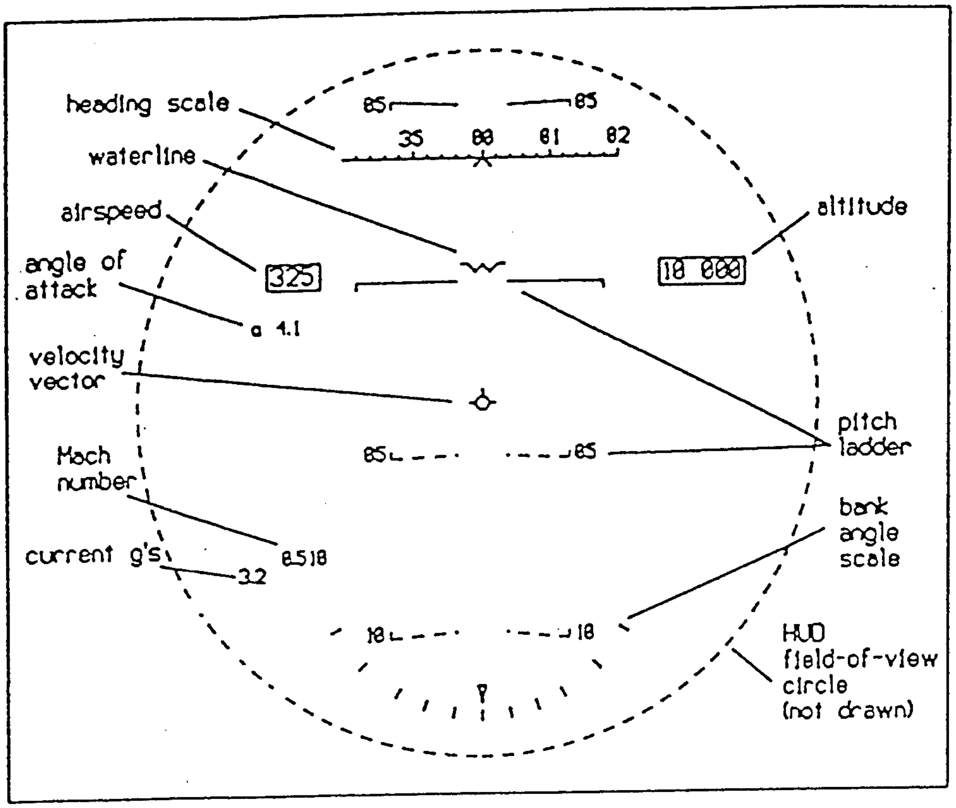
The MS-1 is a fixed-base simulator with a 40 ft visual projection sphere. For this simulation, a 180 deg field-of-view was available. An area-of-interest projector was used to provide a 40 deg field-of-view high-resolution image directly in front of the aircraft's nose. The visual scene was generated by a Martin Marietta C4 system. The worst case time delay for this system (from control input to scene movement) was approximately 115 msec. This delay was comprised of a visual frame time of 16 msec, a visual pipeline delay of 91 msec and a simulation model frame time of 24 msec. For the model examples shown in this Appendix, a total time delay of 107 msec is used. This represents a slight improvement from the worst case and accounts for only half the visual frame time. No visual compensation was used.

The cockpit was a single place generic glass cockpit with a single CRT display. No head-down instrumentation was provided in this simulation.

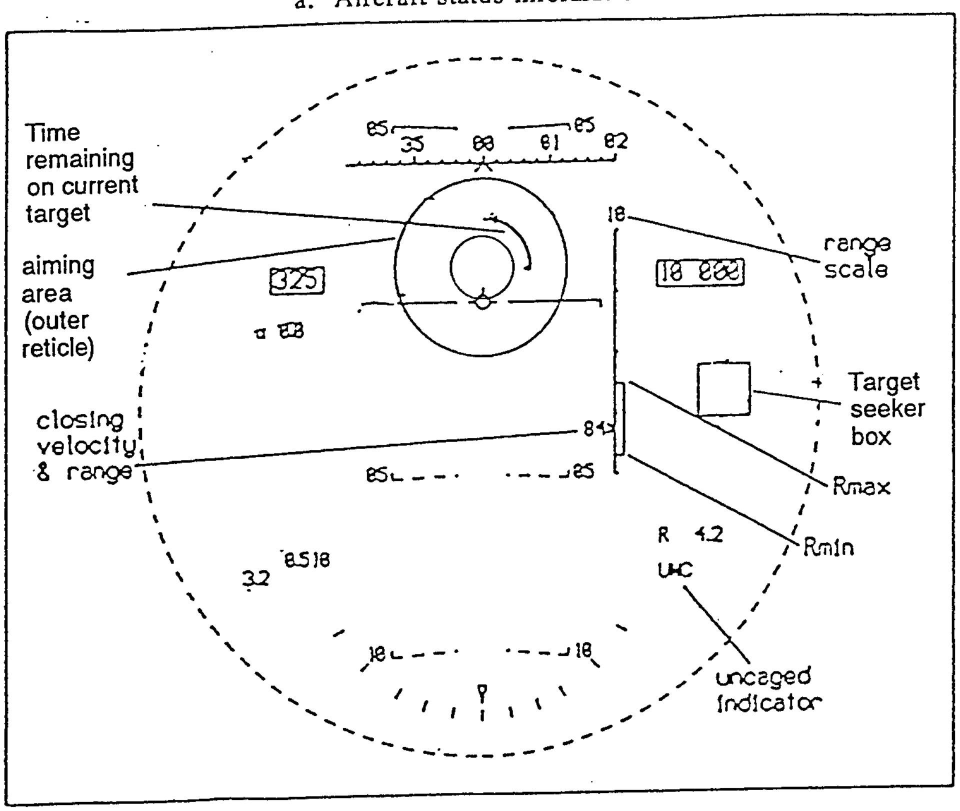
The LAMARS is a six degree-of-freedom motion-base simulator. Common aircraft model and visual software was used in both the MS-1 and LAMARS and, therefore, aircraft model details and visual scenes including HUD imagery were the same in both simulators. The visual field-of-view, however, was more limited in the LAMARS. The total time delays were the same in both simulations. The motion system gains used were those that had been previously used for a simulation involving a high-performance fighter aircraft performing an approach and landing task.

2. Head-Up Display (HUD)

The primary visual cueing in this experiment was provided by the HUD. The HUD imagery used in the experiment was based on an F-15 display, with several modifications to assist in the performance of the evaluation tasks. The HUD is shown in Fig. A-1. It included a conventional pitch ladder with roll attitude provided by both the ladder and the bank angle scale. A velocity vector symbol showed vertical velocity; if vertical velocity exceeded the ranges of the HUD, the symbol would blink and the waterline bar shown in Fig. A-1 would appear. There was no attitude reference in normal flight; zero attitude and



a. Aircraft status information



b. Target and task information.

Figure A-1. Head-Up Display Symbology

flightpath angle corresponded to an imaginary line connecting the tops of the airspeed and altitude boxes. Status information (airspeed, altitude, AOA, Mach number, and load factor) was shown in digital readouts.

In the target acquisition task (described later in this Appendix), target information would pop up on the HUD when the target appeared in the pilot's visual field-of-view. The target information (shown in Fig. A-1b) consisted of a target seeker box that indicated the direction of the target relative to the aircraft and blinked until the target was within the area of the HUD; a target gunsight with inner and outer reticles; a vertical-tape range scale; and a timer "worm." The most useful of these were the target box, outer gunsight reticle, and timer worm. In the F-15 HUD, the worm is usually a range-to-target bar that wraps around the inner reticle. For this simulation, however, it was driven by time and provided information on time remaining to kill the current target: when the worm shrank to zero, the target aircraft would disappear, and shortly thereafter the next target would appear.

C. AIRCRAFT MODEL AND CONFIGURATIONS

1. Bare Airframe Dynamics

The simulated bare airframe dynamics (pitch, heave, and thrust) represented a generic fighter aircraft at an up-and-away flight condition (343 kts, 35000 ft) with flaps and gear retracted. The aircraft model was implemented using linear transfer functions.

The longitudinal bare airframe transfer functions are presented in Table A-1. Three basic open-loop airframe dynamics were used. These represented: a Conventional response-type with a low value of pitch-rate overshoot -- this was the primary pitch configuration; a Conventional response-type with a greater amount of pitch-rate overshoot; and a bare airframe that was used with augmentation (through a simulated flight control system) to represent a Rate Command Attitude Hold (RCAH) system and an Attitude Command Attitude Hold (ACAH) system. Details of the pitch configurations including configuration identifiers are presented in Table A-2.

The lateral bare airframe dynamics were modeled using simple roll-subsidence-only approximations. The primary variables were the roll-mode time constant (T_R) and the roll control sensitivity ($L_{\delta a}$). Specific values of T_R and $L_{\delta a}$ were determined as required for the configurations. The lateral dutch roll mode was well damped and was not a factor in the study. The rudder pedals were not used in the experiment; therefore, the rudder derivatives and transfer functions were not defined. The directional dynamics due to roll were defined assuming perfect turn coordination.

TABLE A-1. LONGITUDINAL BARE AIRFRAME TRANSFER FUNCTIONS

Pitch-rate response:

For Configuration P4

$$\frac{q}{\delta_e} = 8.18 \frac{(0)(0.003)(2.5)^*}{(0)(0.003)(0.51)[0.7,3.5]} \quad \frac{\text{rad/sec}}{\text{rad}}$$

For Configuration P3

$$\frac{q}{\delta_e} = 8.18 \frac{(0)(0.003)(0.51)}{[0.04,0.074][0.7,2.15]} \quad \frac{\text{rad/sec}}{\text{rad}}$$

For Configuration P6 & P8

$$\frac{q}{\delta_e} = 8.18 \frac{(0)(0.0004)(0.55)}{[0.008,0.094](0.57)(3.11)} \quad \frac{\text{rad/sec}}{\text{rad}}$$

Other Responses (Common to all Configurations)

$$\frac{u}{q} = \frac{-32.2 * 0.051}{(0)(0.51)} \qquad \frac{\text{ft/sec}}{\text{rad/sec}}$$

$$\frac{\alpha}{q} = \frac{1}{(0.51)} \qquad \text{rad/rad/sec}$$

$$\frac{u}{\delta_T} = \frac{1}{(1)} \quad \frac{\text{ft/sec}}{\text{rad}}$$ — throttle response

$$^*(a) \equiv (s + a)$$

$$[\zeta,\omega] \equiv (s^2 + 2\zeta\omega s + \omega^2)$$

TABLE A-2. LONGITUDINAL CONFIGURATIONS

Config.	Response Type	K_q (deg/deg/s)	K_θ (deg/deg)	K_I	K_{I_E}	Elevator Actuator Rate Limit (deg/sec)	Comments
P4	Rate	0	0	0	0	∞	Baseline pitch configuration
P4+80	Rate	0	0	0	0	80	Baseline with rate limiting
P4+40	Rate	0	0	0	0	40	
P4+20	Rate	0	0	0	0	20	
P3	Rate	0	0	0	0	∞	High pitch-rate overshoot
P6	ACAH	0.813	2.59	3.2	0	∞	
P8	RCAH	0.813	2.59	3.2	5	∞	

The basic lateral/directional airframe equations are presented below. Euler rates and attitudes were determined through a Quaternion routine using the body-axis rates obtained from the transfer function model.

$$\frac{p}{\delta_a} = \frac{L_{\delta_a}}{(s+1/T_R)}$$

$$r = \frac{g}{V_{t_0}}\phi$$

where:

δ_a - aileron deflection (deg)

p - roll rate (deg/sec)

r - yaw rate (deg/sec)

ϕ - roll attitude (deg)

V_{t_0}- total velocity (ft/sec)

2. Flight Control System

The longitudinal flight control systems (FCSs) were designed by Dave Doman of FIGC, WPAFB. Three longitudinal response-types were simulated. These were: Conventional, Rate Command Attitude Hold (RCAH), and Attitude Command Attitude Hold (ACAH).

The longitudinal FCS block diagram is presented in Fig. A-2. The longitudinal FCS was mechanized to allow the different pitch response-types to be simulated through simple gain changes. Euler pitch rate was used as a rate feedback in order to maintain pitch attitude during a turn. All integrators within the control loop were limited integrators with limits corresponding to the elevator position limit. A generic second-order actuator model was used to represent both the aileron and elevator actuators. Figure A-3 presents a block diagram of the simulated actuator model.

The lateral (roll) flight control system block diagram is presented in Fig. A-4. The loop structure is essentially similar to the pitch FCS with roll rate and roll attitude feedbacks. The lateral dynamics were representative of a Rate Command response-type.

The ailerons and elevators were position limited at 0.6 rad or 34.4 deg.

3. Pitch Configurations

The longitudinal configurations are listed in Table A-2. The flight control system gains given in Table A-2 refer to the block diagram gains shown in Figs. A-2 and A-3.

The primary pitch configuration was the conventional response-type (P4) that was mechanized without the FCS (open-loop). The open-loop dynamics of this configuration were tailored to represent a lightly augmented system. This approach greatly simplified the implementation of the models in the simulation. The open-loop pitch dynamics for Configuration P4 are presented in Table A-1. Another Conventional response-type configuration with a greater amount of pitch-rate overshoot than Config. P4, Config. P3, was designed to investigate the effect of pitch-rate overshoot on flying qualities. The open-loop pitch dynamics for Config. P3 are also presented in Table A-1. The Attitude Command Attitude Hold (ACAH) and Rate Command Attitude Hold (RCAH) configurations were mechanized using a different bare airframe (see Table A-1). The FCS gains that define the RCAH and ACAH configurations are provided in Table A-2.

The pitch attitude bandwidths of the basic pitch configurations (P4, P3, P6, and P8) were Level 1. Pitch attitude frequency responses and time histories for these configurations, presented in

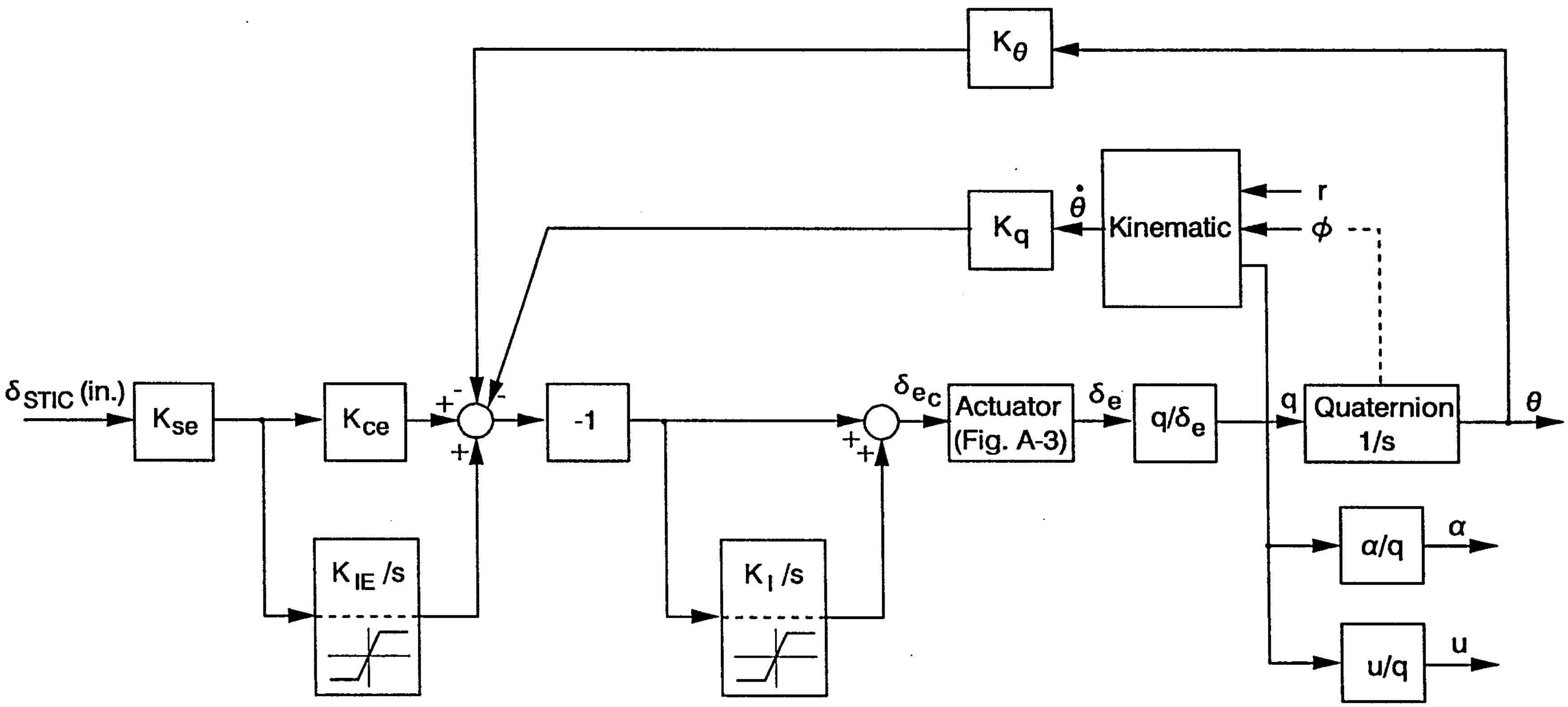
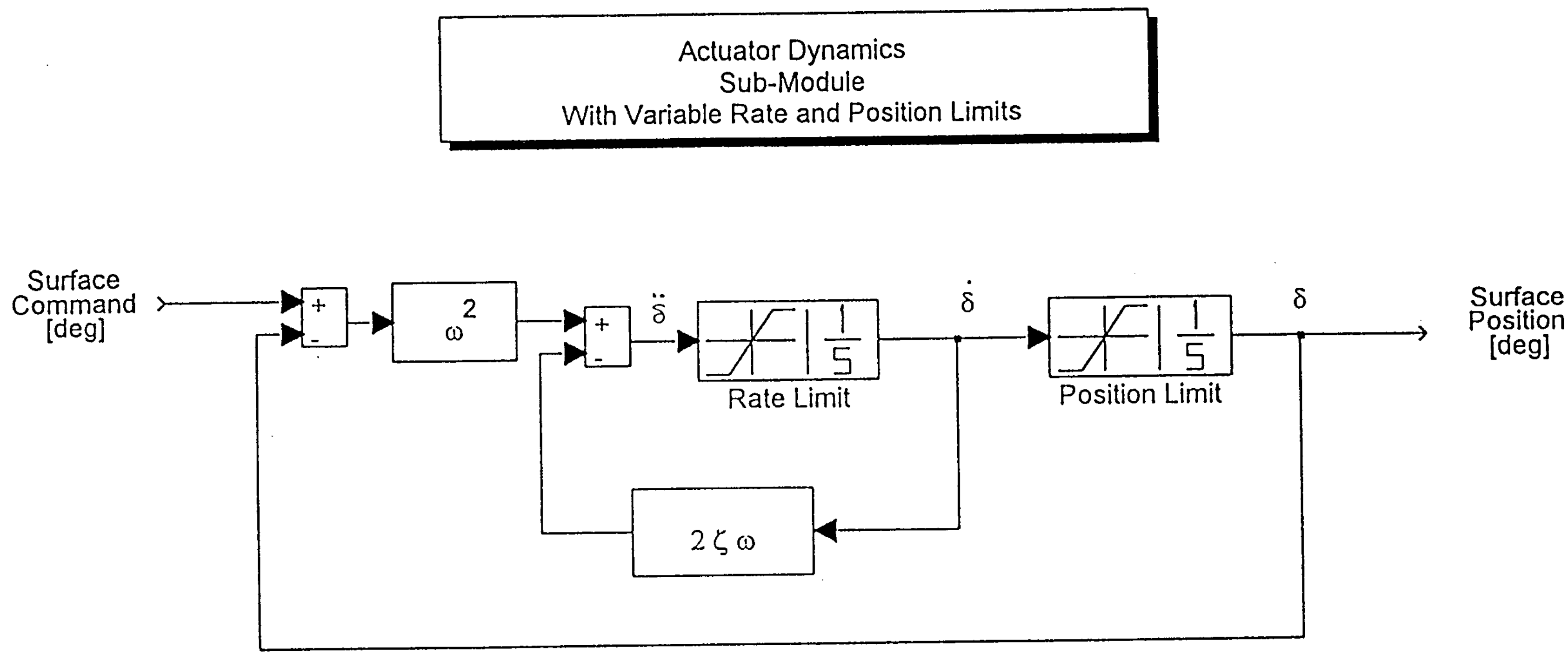


Figure A-2. Block Diagram of Actual Longitudinal FCS



Note: The actuator structure is the same for the aileron and elevator actuators.

ζ - damping ratio

ω - frequency (rad/s)

Figure A-3. Elevator/Aileron Actuator Model

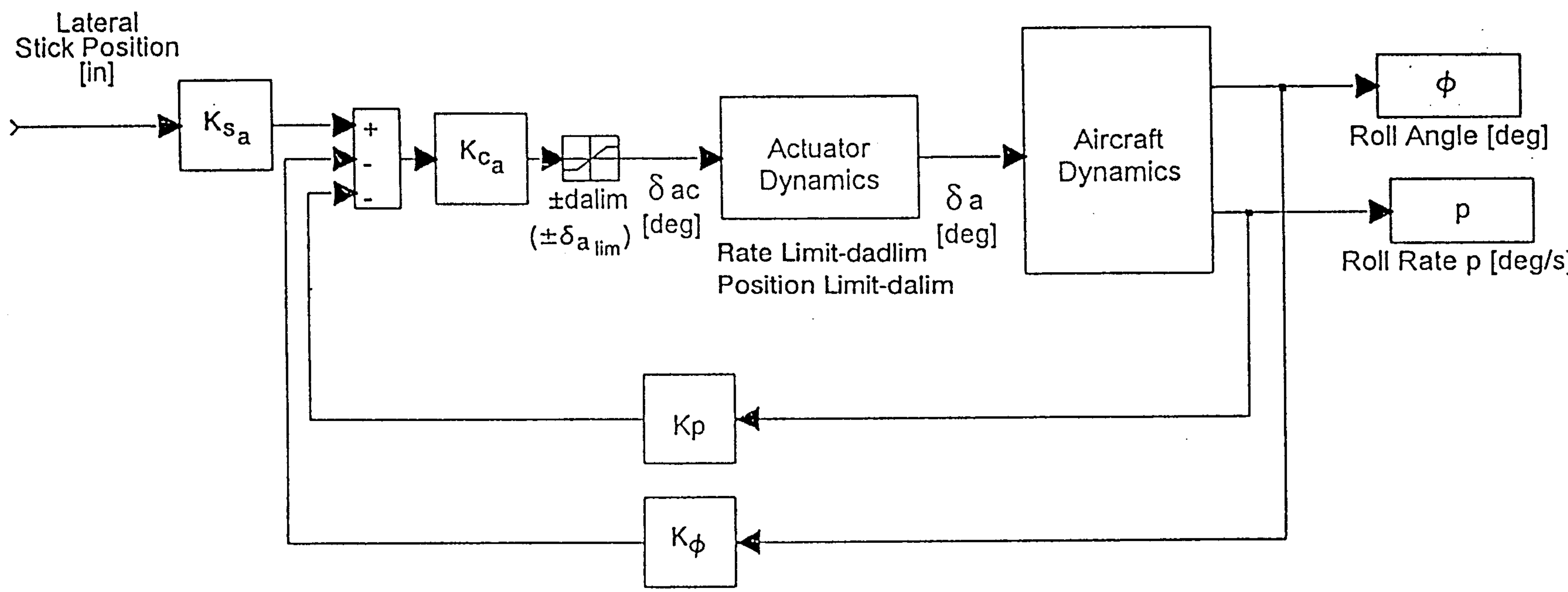


Figure A-4. Roll FCS Block Diagram

Figs. A-5 through A-8, illustrate the basic differences in the response characteristics of these three configurations. The effect of the simulation time delay of 107 msec and the longitudinal stick dynamics (discussed later) are included in these responses. For the closed-loop configurations only the 24 msec simulation model frame time was included within the loop as a delay.

Four of the longitudinal configurations investigated the effect of actuator rate limiting on pitch flying qualities. These were: the basic configuration with an unlimited rate actuator (Config. P4) and three configurations with varying amounts of rate limiting (Configs. P4+20, P4+40, P4+80 -- see Table A-2).

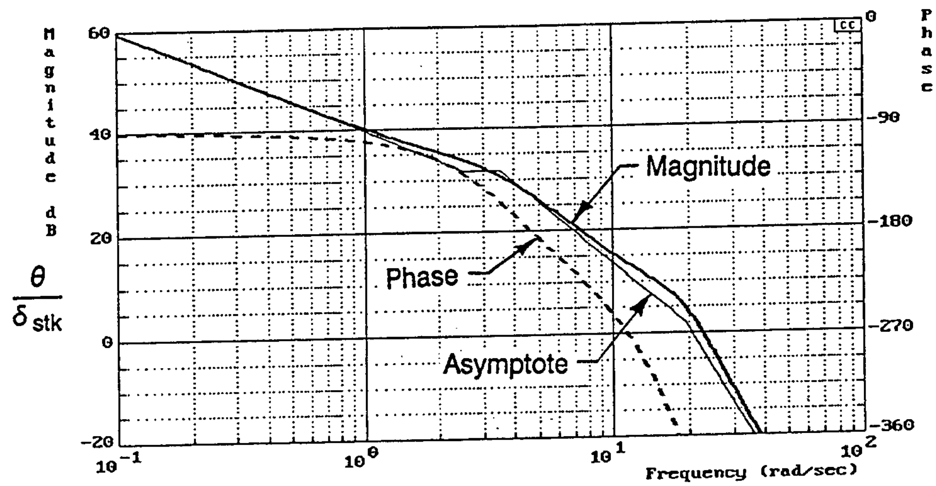
The theoretical pitch attitude quickness that may be achieved with the four primary pitch configurations P4, P4+80, P4+40, and P4+20 are presented in Fig. A-9. Figure A-9 shows the appropriate pitch response parameters $q_{pk}/\Delta\theta_{pk}$ and $\Delta\theta_{min}$ that result from elevator pulse inputs of 21.5 deg magnitude. The input magnitude represents the maximum elevator input that was achieved in the simulation with the maximum longitudinal stick travel allowed by the hardware (approximately 5 inch aft) and the stick sensitivities used (4.3 deg elevator per inch of stick deflection). The input pulse width was varied to obtain the different values of $\Delta\theta$ required. The boundaries shown in Fig. A-9 represent the theoretical maximum pitch attitude quickness that may be achieved. It also shows the degradation in attitude quickness caused by the actuator rate limiting.

4. Roll Configurations

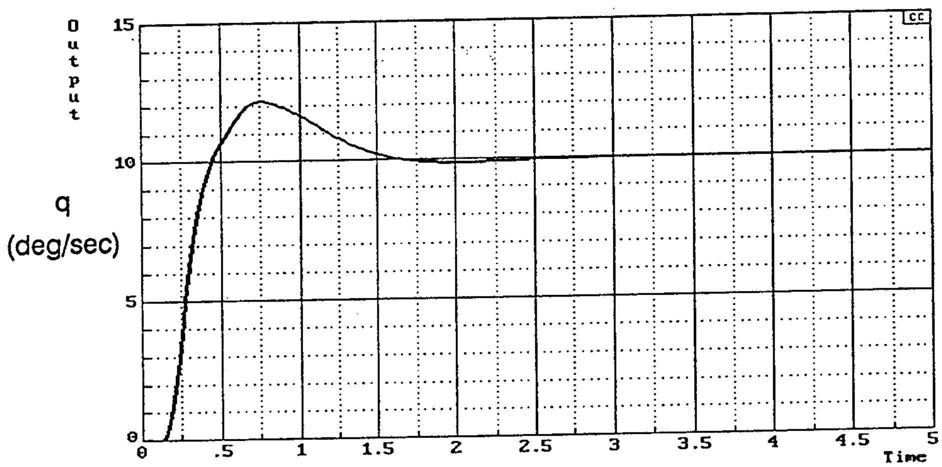
The lateral configurations are listed in Table A-3. The FCS gains given in Table A-3 refer to the block diagram gains in Figs. A-3 and A-4.

In the lateral configurations, the bare airframe (roll mode and control power), FCS gains, and aileron actuator rate limit were varied to systematically investigate the handling qualities boundaries for roll attitude quickness. Some configurations were also tailored to investigate any differences in flying qualities between augmented and unaugmented aircraft with the same roll dynamics and actuator rate limit. The roll dynamics of the augmented configuration (R16, for example) will be the same as those of the equivalent unaugmented (R7, for example) configuration only when the actuator is not limited. When the actuator is limited, the dynamics will be different. Details of the design of the roll configurations are presented below. Brief descriptions of the configurations are also included in Table A-3.

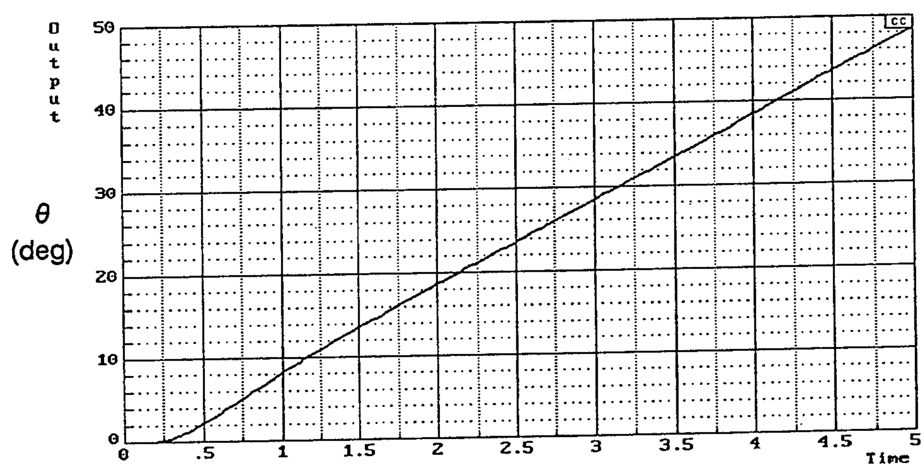
Figure A-10 presents the theoretical attitude quickness that may be achieved with each configuration. These plots show the maximum achievable attitude quickness for each configuration (within the constraints of the criterion). The plots were generated by inserting a pulse lateral stick



a) Frequency Response of θ to Longitudinal Stick

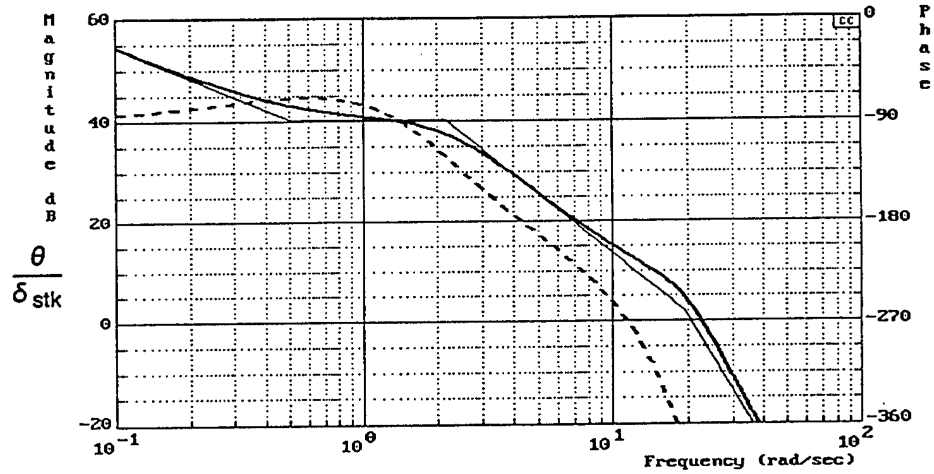


b) Step Response of q to Longitudinal Stick

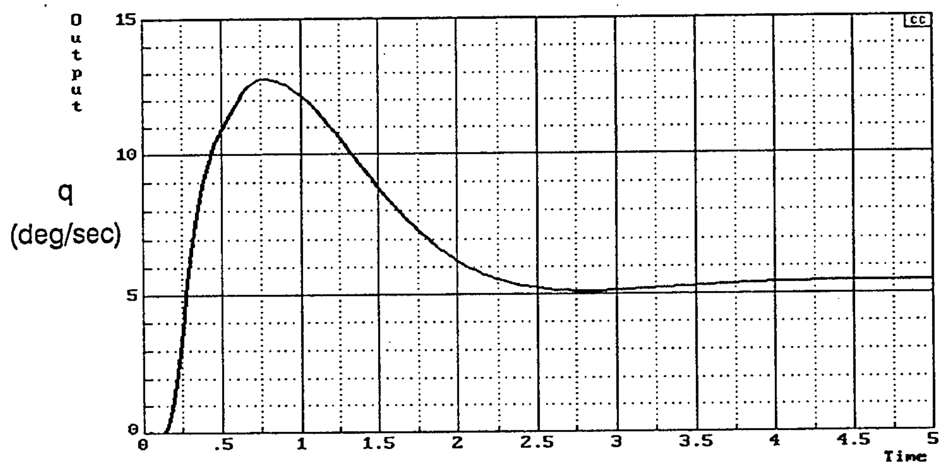


c) Step Response of θ to Longitudinal Stick

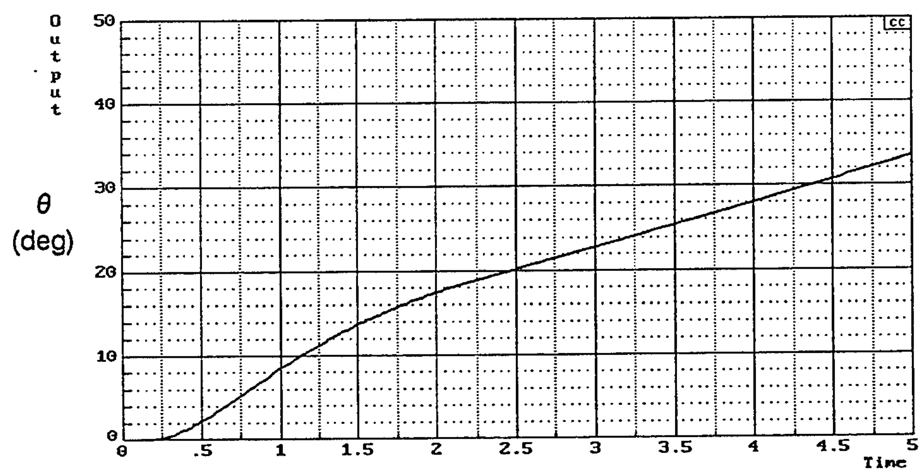
Figure A-5. Response Characteristics of Config. P4



a) Frequency Response of θ to Longitudinal Stick

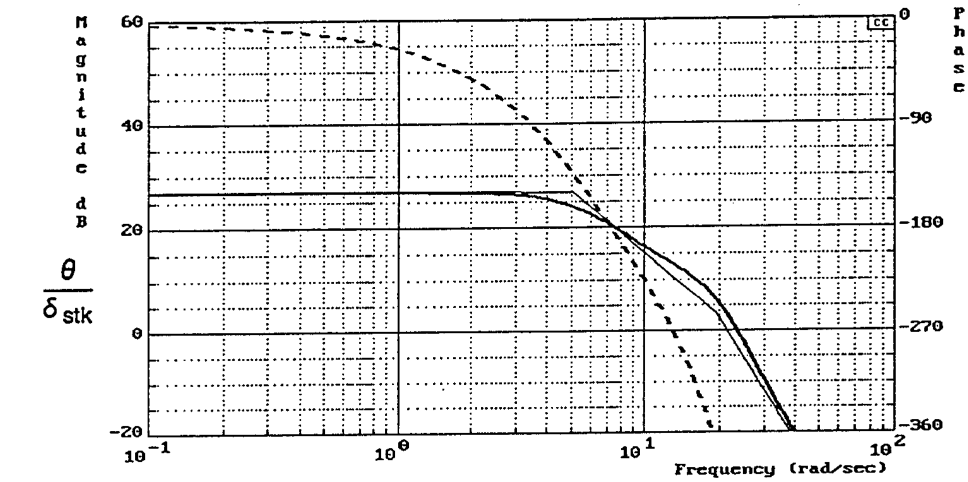


b) Step Response of q to Longitudinal Stick

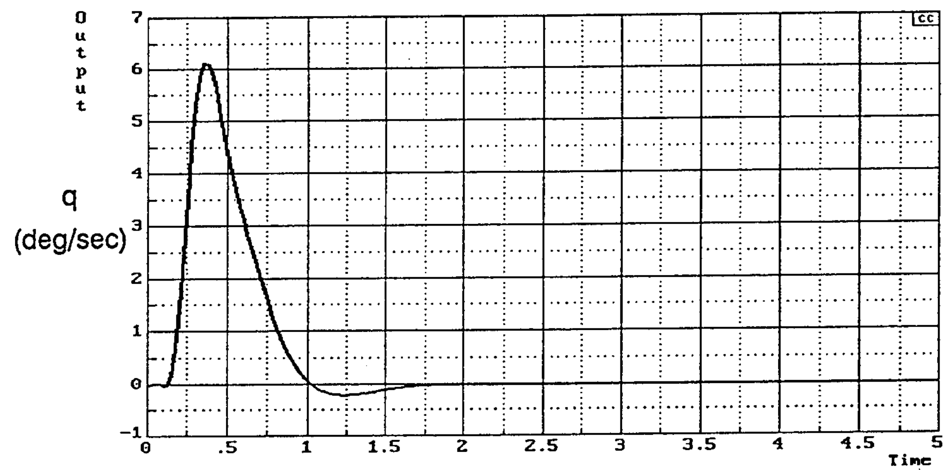


c) Step Response of θ to Longitudinal Stick

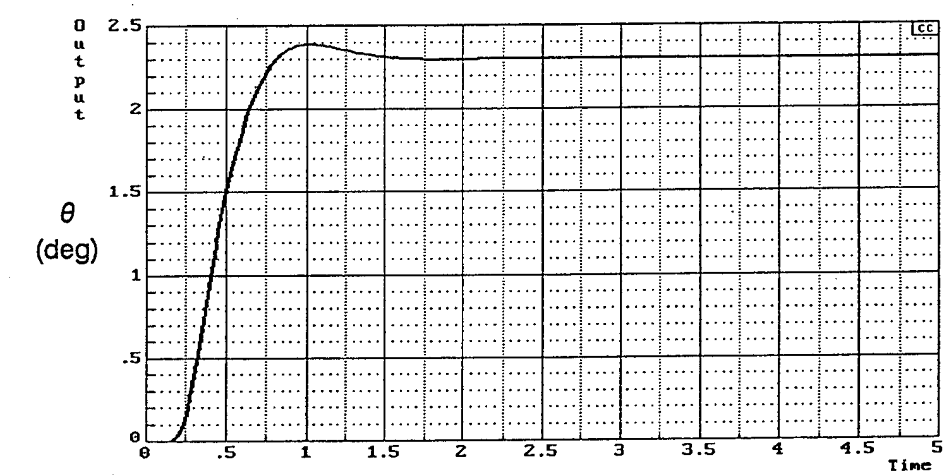
Figure A-6. Response Characteristics of Config. P3



a) Frequency Response of θ to Longitudinal Stick

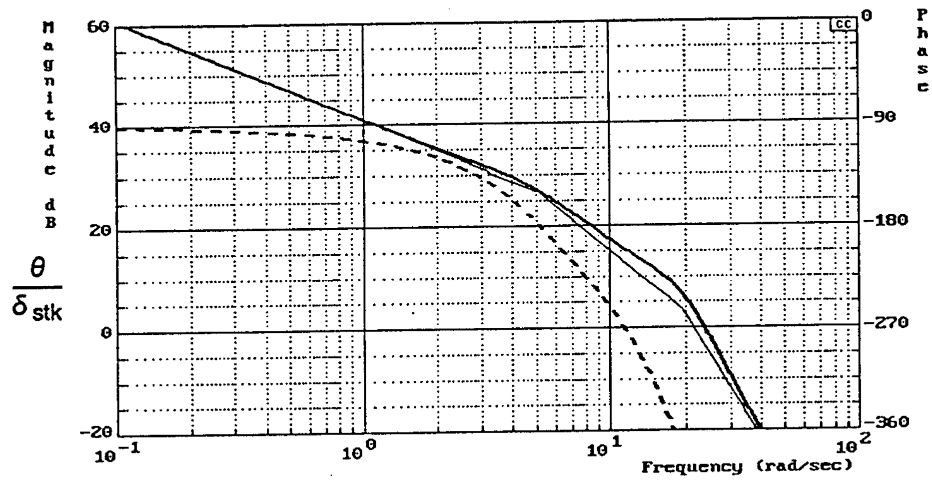


b) Step Response of q to Longitudinal Stick

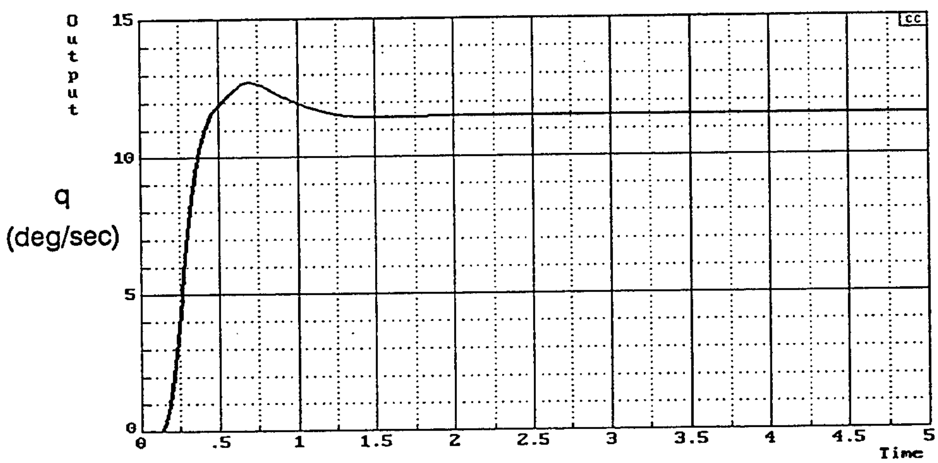


c) Step Response of θ to Longitudinal Stick

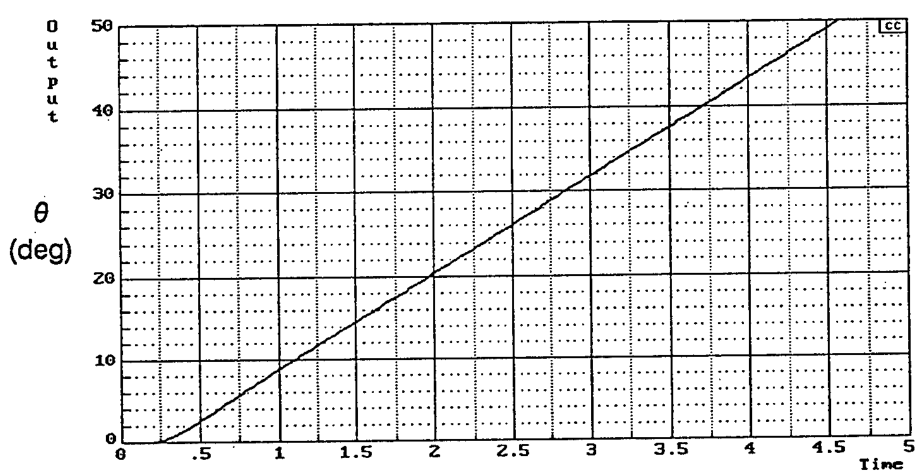
Figure A-7. Response Characteristics of Config. P6



a) Frequency Response of θ to Longitudinal Stick



b) Step Response of q to Longitudinal Stick



c) Step Response of θ to Longitudinal Stick

Figure A-8. Response Characteristics of Config. P8

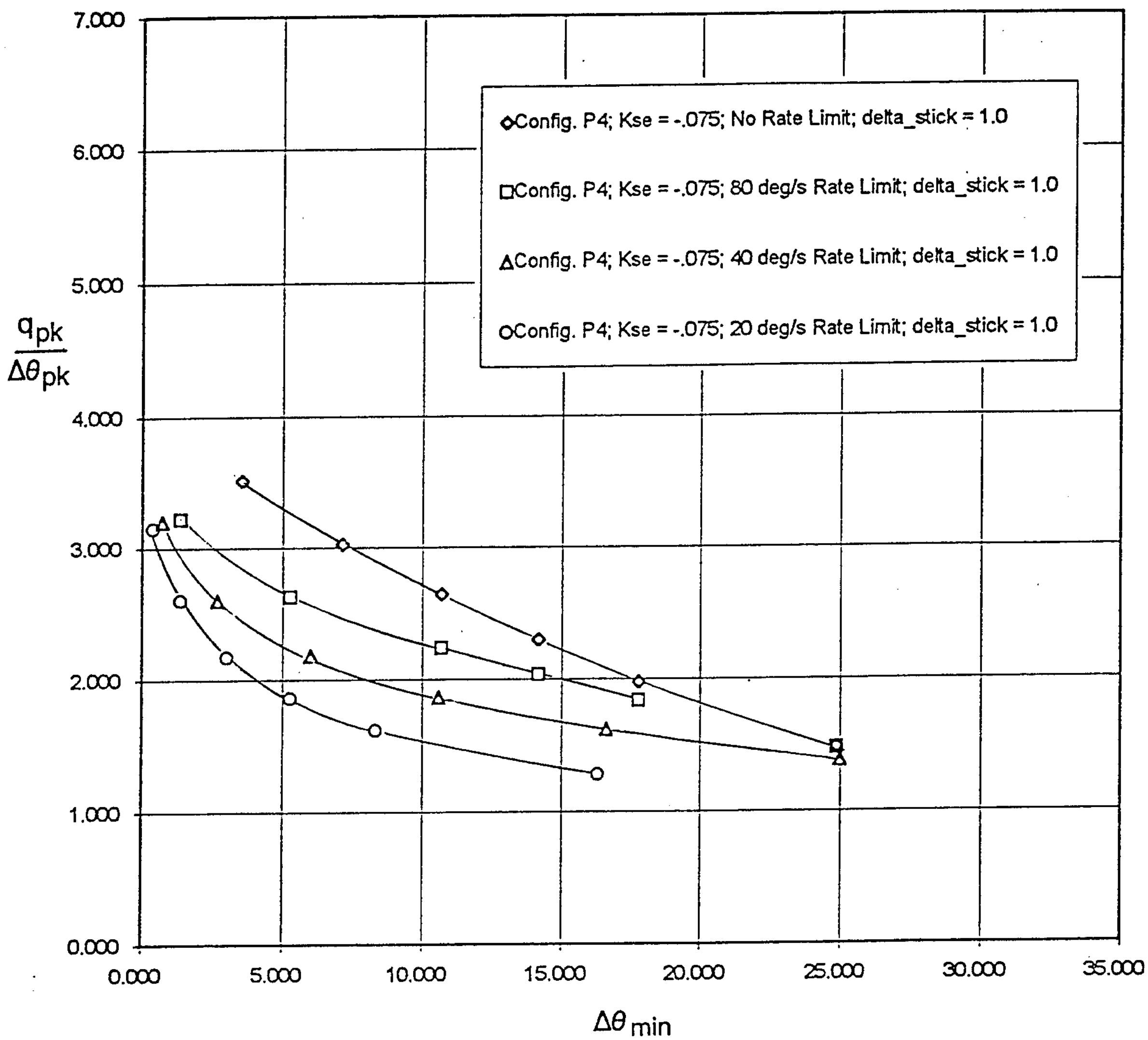


Figure A-9. Maximum Theoretical Pitch Attitude Quickness for Simulated Pitch Configurations

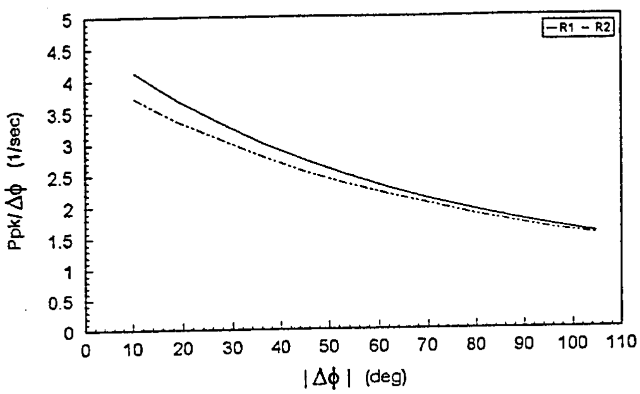
TABLE A-3. LATERAL CONFIGURATIONS

Symbol:	K_p	$\dot{\delta}_{a_{lim}}$	L_{δ_a}	T_R	$1/T_R$ (unaugmented)	$1/T_R$ (effective Augmented)	Comments
Name:	K_p	dadlim	Lda	TR	1/TR		
Config #	[deg/(deg/sec)]	[deg/sec]	[(deg/sec²)/deg]	[sec]	[rad/sec]	[rad/sec]	
1	0	∞[1]	25	0.2	5	5	Baseline unlimited cases with and without augmentation
2	0.152	∞[1]	20.7	1	1	5	
3	0	40	6	0.2	5	5	Variations in aileron control effectiveness with a rate limit
4	0	40	25	0.2	5	5	
5	0	40	100	0.2	5	5	
6	0	20	25	0.2	5	5	Variations in rate limit with an unaugmented aircraft with a high $1/T_R$
7	0	40	25	0.2	5	5	
8	0	80	25	0.2	5	5	
9	0	20	17	0.333	3	3	Variations in rate limit with an unaugmented aircraft with medium $1/T_R$
10	0	40	17	0.333	3	3	
11	0	80	17	0.333	3	3	
12	0	20	11	1	1	1	Variations in rate limit with an unaugmented aircraft with a low $1/T_R$
13	0	40	11	1	1	1	
14	0	80	11	1	1	1	
15	0.152	20	20.7	1	1	5	Variations in rate limit with a high effective augmented $1/T_R$
16	0.152	40	20.7	1	1	5	
17	0.152	80	20.7	1	1	5	

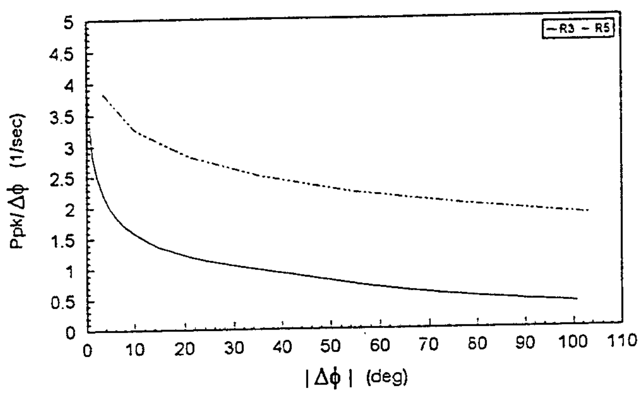
[1]Here ∞ indicates a very large value was set (10^6); equivalent to no limit.

For All Cases Here:

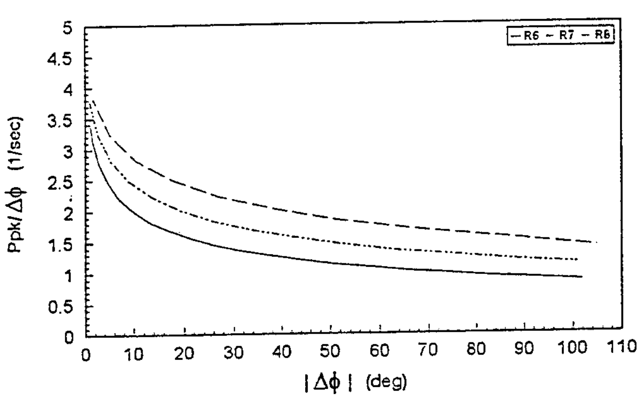
$K\phi$	=	0 deg/deg	
K_{ca}	=	1 deg/deg	
ω_{δ_a}	=	75 rad/sec	(actuator natural frequency)
θ_{δ_a}	=	0.7	(actuator damping ratio)
$\delta_{a_{lim}}$	=	∞	(very large—equivalent to no limit)
K_{sa}	=	Pilots selected for some evaluations (nominally 1.0)	



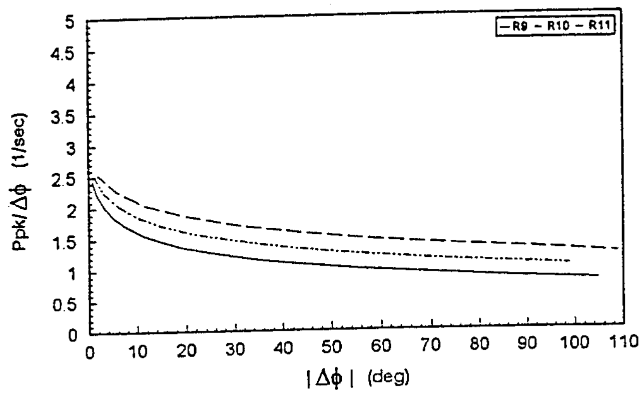
a) Configurations R1 & R2



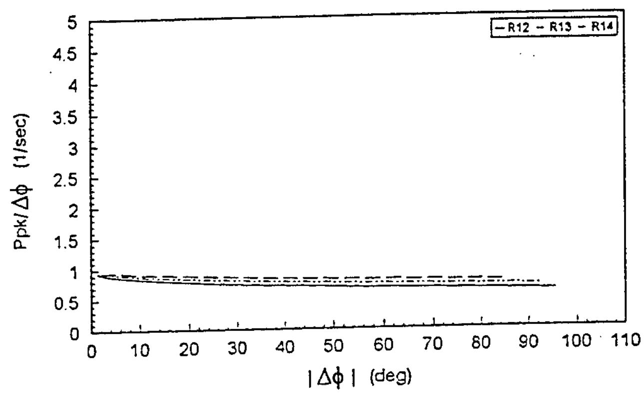
b) Configurations R3 & R5



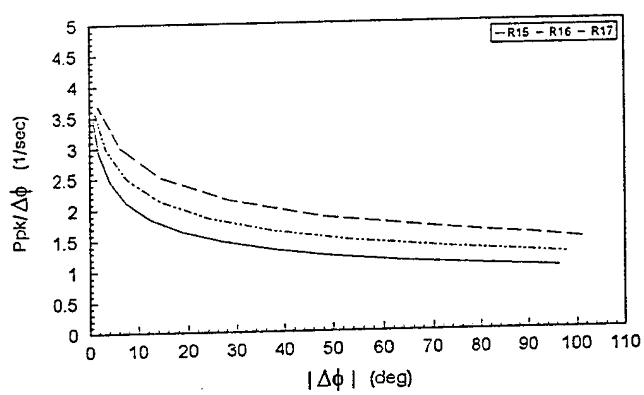
a) Configurations R6, R7, & R8



d) Configurations R9, R10, & R11



e) Configurations R12, R13, & R14



f) Configurations R15, R16, & R17

Figure A-10. Theoretical Attitude Quickness for the Roll Configurations

command of magnitude equivalent to 34.4 deg of aileron (maximum allowed by the aileron surface position limit). The resulting bank angle change and peak roll rate were measured and used to generate the plots. The pulse width was progressively increased from a small value in order to achieve a progressively increasing bank angle change. The effect of the lateral stick dynamics and simulation time delay on attitude quickness was investigated and found to be negligible. These effects are not included in these plots.

Brief descriptions of the configurations are provided in Table A-3.

D. STICK CHARACTERISTICS

A McFadden center stick was used for pitch and roll control. Stick displacement sensing was used by the flight control system. The longitudinal and lateral stick characteristics are shown below.

The stick dynamics were measured by Dave Doman of FIGC, WPAFB. The dynamics were measured by fitting a transfer function to a stick "step response." A "step response" was obtained by holding the stick at its travel limit and releasing it. The resulting time history of stick displacement was similar to a step response. A third-order transfer function was required to completely model the stick response. Specifically, a first-order dipole pair was required to model a stick displacement "trimming" action seen in the responses. This first-order dipole is most probably due to non-linearities in the stick feel system and would not be noticed by a pilot performing the types of maneuvers simulated in this experiment. The longitudinal and lateral dynamics shown are averaged values for each direction of travel in each case.

$$\text{Long:} \quad \frac{\delta_{e_s}}{F_{e_s}} = \frac{(s/0.45 + 1)}{(s/0.31 + 1)} \frac{0.42}{\left[\dfrac{s^2}{(19.2)^2} + \dfrac{2(0.36)s}{(19.2)} + 1\right]} \quad \frac{\text{in}}{\text{lb}}$$

$$\text{Lat:} \quad \frac{\delta_{a_s}}{F_{a_s}} = \frac{(s/0.42 + 1)}{(s/0.28 + 1)} \frac{0.30}{\left[\dfrac{s^2}{(22.5)^2} + \dfrac{2(0.34)s}{(22.5)} + 1\right]} \quad \frac{\text{in}}{\text{lb}}$$

The longitudinal and lateral breakout forces were 0.5 lbs and 1.5 lbs, respectively.

Stick force could not be measured on the simulators. Direct measurement of the stick gradients were, therefore, not possible. The stick, however, was the same as implemented in a previous experiment on the LAMARS (Ref. A-1) and the values of gradient and breakout stated in this Appendix were obtained from Ref. A-1.

A position control quadrant throttle was available for airspeed control.

E. EVALUATION TASKS

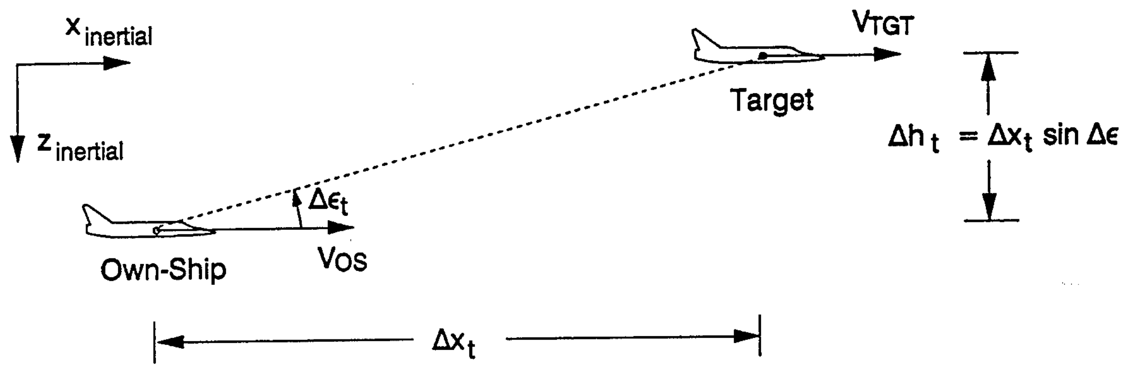
Three evaluation tasks were used in the experiment. Two of these were a simulated target acquisition task and a ground attack task that were specifically designed to evaluate handling qualities during aggressive gross maneuvering. The third task was a simulated formation flying/air-refueling task that was designed to evaluate the effect of pitch response-type for the air-refueling and formation flying MTEs and similar tasks that require precise pitch control. There was no simulated turbulence for any of the tasks.

1. Target Acquisition Task

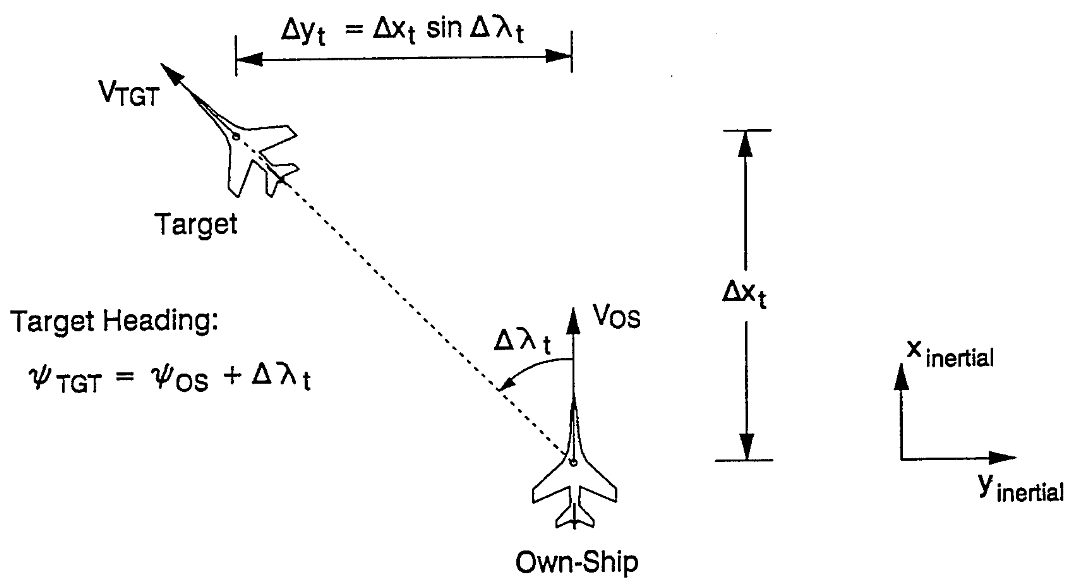
The target acquisition task was tailored to evaluate moderate amplitude handling qualities (attitude quickness). This was the primary evaluation task in this experiment. The task was a modified version of one used to examine the directional flying qualities of a helicopter in Ref. A-2.

The task required the pilot to rapidly maneuver (in pitch and roll) to acquire a target aircraft and track it for a sufficient period of time to satisfy a firing solution. All the pilot cueing for the task was provided by the HUD as described previously in this Appendix. The target appeared at different locations in the pilot's field-of-view and disappeared once the firing solution has been achieved (i.e., shot-down or killed). Once "killed" at one location, the target aircraft reappeared at another location. Successive target acquisitions were conducted in groups of six and each group was labeled as a single run. The initial target locations were determined at the simulation checkout stage to elicit varying amounts of bank angle change ranging from small to large. The specific events that comprise this task are outlined below.

1. Target aircraft materializes in the subject pilot's field-of-view. The target location geometry is specified in Fig. A-11. The range to the target (Δx_t) as well as the initial elevation ($\Delta\varepsilon_t$) and azimuth ($\Delta\lambda_t$) angles to the target were predetermined. The initial range to the target was 3000 ft and both $\Delta\varepsilon_t$ and $\Delta\lambda_t$ were varied within a range of ±20 deg. The target was initialized to the present speed of the subject aircraft (own-ship, in Fig. A-11) and flew straight and level, at a constant speed, on cold heading (target heading equal to angle off) as shown in Fig. A-11b.



a) Elevation ($V_{TGT} = V_{OS}$ (t = current time))



b) Azimuth ($V_{TGT} = V_{OS}$ (t = current time))

Figure A-11. Target Location Geometry

2. When the target appears and is spotted, the subject pilot was required to aggressively alter heading and attitude to acquire the target. An aural cue (a low tone) was provided to warn the pilot that the target had appeared. To obtain a firing solution, the pilot was required to continuously maintain the nose of the aircraft (using the aiming reticle on the HUD) within specific values of $\Delta\varepsilon_t$ and $\Delta\lambda_t$ (aiming criteria -- ±2 deg each) for 4 seconds. An aural cue (a high tone) was used to indicate that the target was within the desired aiming criteria. The aural cue changed from a solid to an intermittent tone when the pilot maintained the target within the aiming criteria for the required amount of time. The pilot would then squeeze the missile release button on the stick to "kill" the target and the target would disappear. If the pilot was unable to achieve a firing solution within 15 sec, the target would disappear automatically. A timer worm on the HUD (described earlier) provided the pilot with a cue on the time remaining for the acquisition.

3. The target reappeared after a short length of time (that varied between 2 and 4 sec) at the next specified location in the pilot's field-of-view and the acquisition was repeated. The pilot was instructed to use the interval between the disappearance and reappearance of the target to return the aircraft to a level attitude. The speed of the target was matched to the current speed of the own-ship.

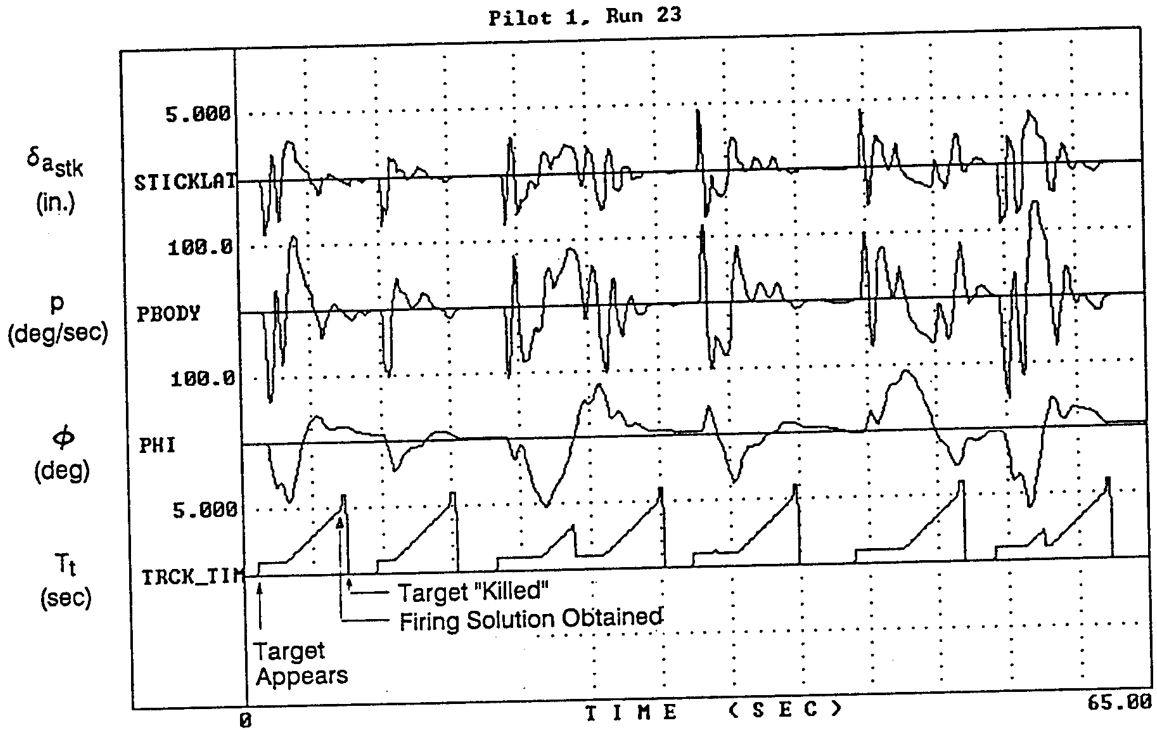
Each run sequence consisted of six separate target acquisitions. The initial elevation and azimuth angular offsets of the targets are listed in Table A-4. The sequencing of targets was randomly varied to prevent the pilot from learning a sequence and anticipating the location of the target before it materialized. The pilots were advised that the primary intent of the task was to evaluate the gross maneuvering portion of the task and not the final, fine tracking,

Time histories of lateral stick, roll rate, bank angle, aiming error, and time-on-target (T_t) for a sample run are shown in Fig. A-12 and illustrates the task.

The initial altitude and airspeed of the aircraft at the start of a run was 35,000 ft and 343 kts, respectively. The target was a laser projection of a F-15 aircraft.

TABLE A-4. TARGET INITIAL CONDITIONS

Target No.	1	2	3	4	5	6
Elevation $\Delta\varepsilon_t$ (deg)	0	5	20	10	20	0
Azimuth $\Delta\lambda_t$ (deg)	10	5	10	5	15	20



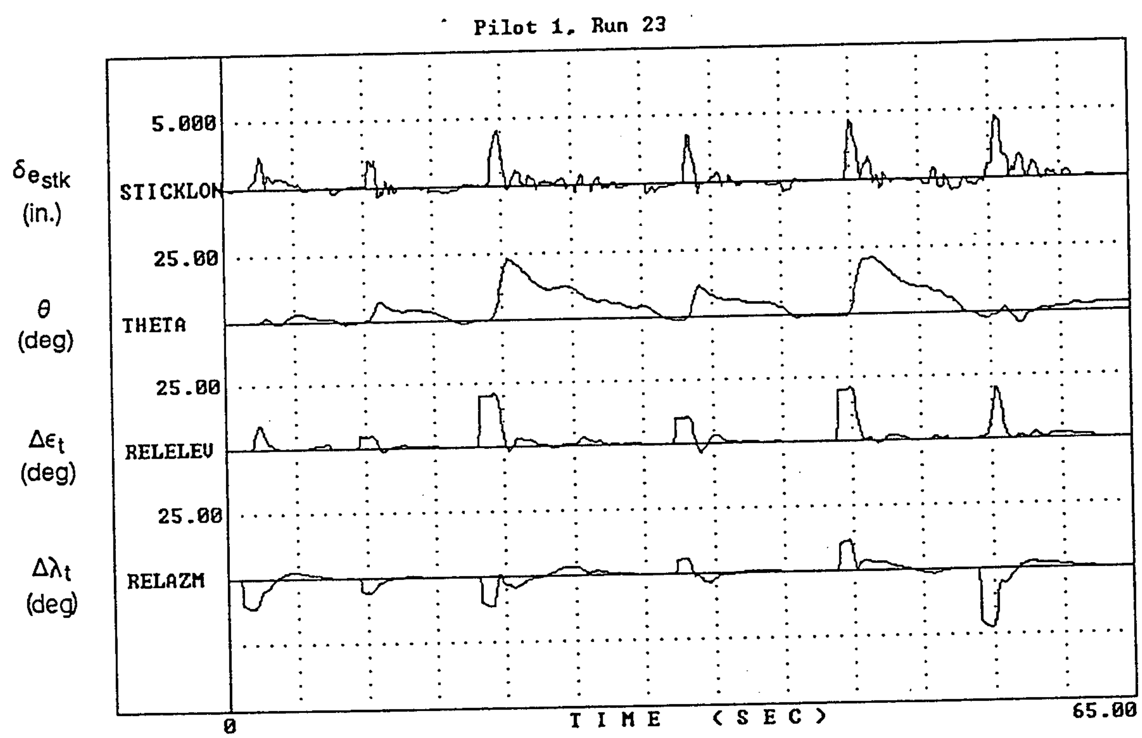


Figure A-12. Sample Run Time History

The performance requirements for the task were as given below.

Desired Performance:

- "Kills" on all six targets.
- No more than one overshoot of the target in final tracking (loss of tone). (Momentary activation of the tone during initial maneuvering into tailchase should be ignored.)
- No tendency for pitch and roll oscillations.

Adequate Performance:

- "Kills" on at least four of the six targets.
- No more than two overshoots of the target in final tracking (loss of tone). (Momentary activation of the tone during initial maneuvering into tailchase should be ignored.)
- No tendency for pitch and roll oscillations.

2. Ground Attack Task

The ground attack task simulated the final rollout and dive toward a specific point on the ground. A runway was used as a reference point and to provide a performance reference for the task. The run started from straight and level flight, at an airspeed of 343 kts, offset laterally from, but with heading aligned with, the runway. When the simulation starts, the pilot was instructed to *immediately* execute a rapid roll to line up with the runway and then descend toward the runway threshold. The objective was to pass over the runway threshold at low altitude and initiate a climbout. The run ended as soon as the climbout began.

Evaluations were performed from four different starting positions (two near, two far, and on either side of, the runway) for each configuration before a rating was given. The starting positions are shown in Fig. A-13. Additional runs were performed (and encouraged) when necessary to properly formulate a pilot opinion. The performance requirements for the task are given below.

Desired Performance:

- Achieve desired performance on at least three out of four runs.
- Altitude over the runway threshold between 50 and 150 ft AGL; minimum altitude of 50 ft.
- Heading over the runway threshold within 5 deg of runway heading.
- Bank angle over the runway threshold within 10 deg of level attitude.
- Lateral position over the runway threshold within runway edges.
- No tendency for pitch or roll oscillations.

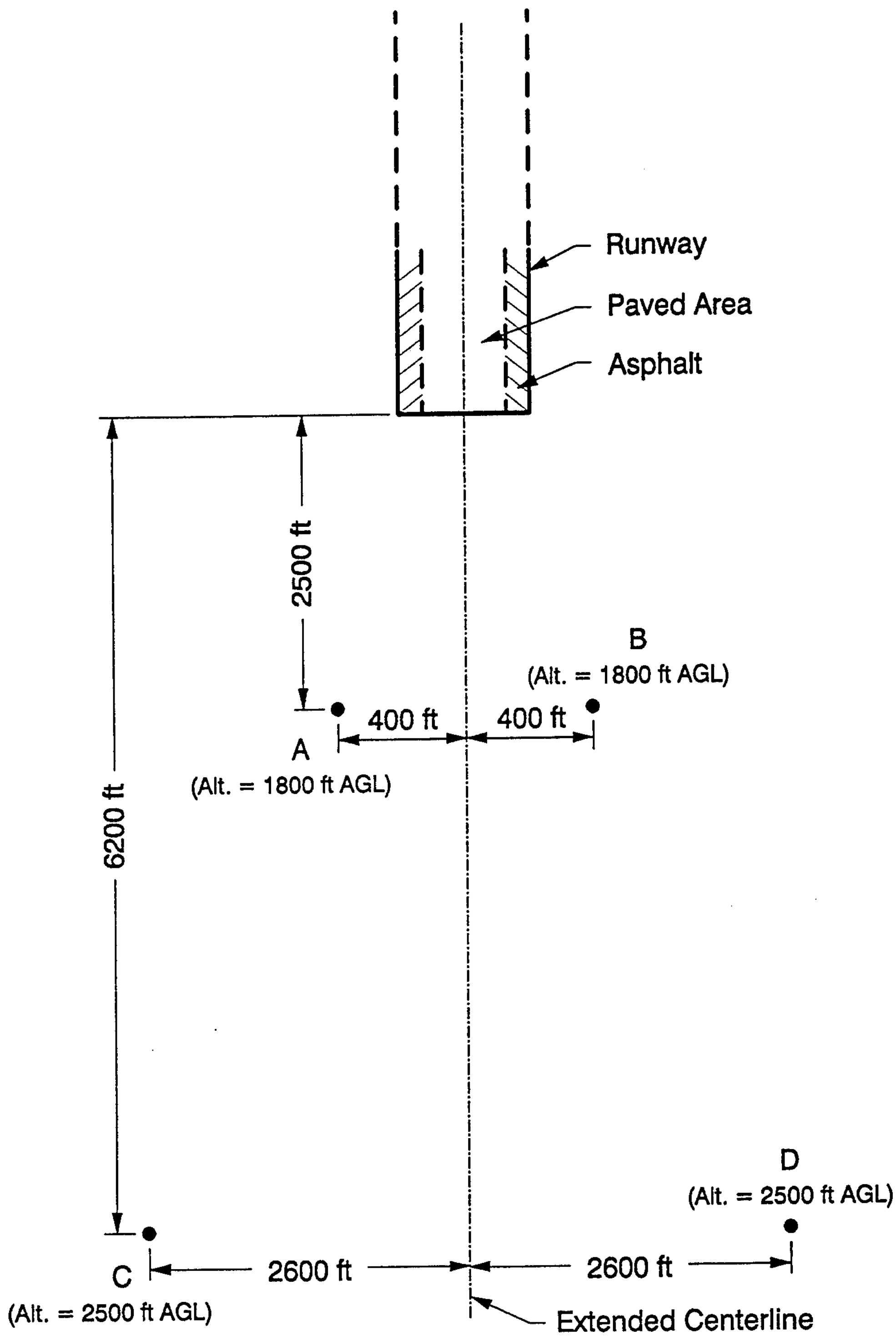


Figure A-13. Initial Conditions for the Ground Attack Task

Adequate Performance:

- Achieve adequate performance on at least three out of four runs.
- Altitude over the runway threshold between 10 and 200 ft AGL; minimum altitude of 10 ft.
- Heading over the runway threshold within 10 deg of runway heading.
- Bank angle over the runway threshold within 20 deg of level attitude.
- Lateral position over the runway threshold within asphalt (black runoff areas on either side of runway).
- No tendency for pitch or roll oscillations.

To aid the pilot in judging performance, parameters such as altitude, heading and bank angle could be frozen in time and stored by the software when the trigger on the control stick was depressed. The pilot would depress the trigger when passing over the runway and the relevant performance parameters would be read back to the pilot at the end of each run.

3. Simulated Formation Flying/Air-Refueling

This task simulated the precision required for aerial refueling or precision formation flying. It was not designed to reproduce the details of an actual air refueling task. The aircraft was initialized in a trail formation position with a "tanker" aircraft image, flying at the same airspeed. The simulated tanker aircraft was a Boeing 747. The objective of the task was to maneuver to a close trail position directly behind the tanker (pre-contact position), and then perform a lateral sidestep maneuver to the left or right (pilot's choice), line up directly behind the outermost engine pod on the tanker, and stabilize. The aircraft was deemed to be stabilized when the engine pod was located and held within the outer reticle on the HUD with no apparent significant drift. There was no simulated turbulence or wake from the tanker.

The pilot was encouraged to make as many sidesteps as required to form an opinion on the flying qualities. Lateral and vertical positions relative to the tanker were determined by reference to the gunsight reticle. Due to the low fidelity of the tanker image, distance from the tanker was difficult to judge and the pilot was instructed not to weigh it heavily in the evaluation. The task was not tightly constrained and performance judgement was entirely subjective. The performance guidelines are given below.

Desired Performance:

- Complete each transition and hold the tanker engine pod within one-half-width of the outer reticle on the HUD for 30 sec.
- No tendency for pitch or roll oscillations.

Adequate Performance:

- Complete each transition and hold the tanker engine pod within the outer reticle on the HUD for 30 sec.
- No tendency for pitch or roll oscillations.

F. EVALUATION PROCEDURES AND DATA GATHERING

Almost all the evaluations were performed on the fixed-base MS-1 simulator. This was primarily due to motion fidelity concerns associated with large amplitude maneuvering on a full motion simulator. A few configurations were also evaluated on the LAMARS by one pilot using the gross maneuvering tasks in order to assess the effect of motion on perceived flying qualities. These motion-base evaluations were only performed after this particular pilot had completed evaluations on the MS-1. Comments from the pilot that the motion cues seemed inappropriate (particularly for the ground attack task) indicated that the decision to rely on the fixed-base simulator was appropriate.

The primary evaluation task was the target acquisition task and all pilots were generally exposed to all the configurations with this task before moving on to the other tasks. Each pilot was allowed as much training time as necessary to become familiar with the tasks and the level of precision and aggressiveness required. With the target acquisition task, at least two runs were performed before assigning a pilot rating. With the ground attack task, at least one set of four runs (as described earlier) was performed before assigning a rating. The pilots were encouraged to request additional runs when necessary for formulating a clear opinion on a configuration.

With the formation flying task, the pilots were informed that it was unconstrained and that the stated performance criteria for the task were purely advisory. They were encouraged to devise their own performance criteria, if they deemed it appropriate. All the pilots, however, found the performance guidelines to be suitable for assessing flying qualities in this task.

The pilots were allowed to select control sensitivity in pitch and roll. All pilots found the nominal control sensitivities (selected by the first evaluation pilot) to be satisfactory. In the initial series of runs for a pilot on a given day, configurations were presented in increasing order of difficulty in order to "calibrate" the pilot in terms of required compensation. After this initial stage (usually two or three configurations), configurations were presented in a random order.

Pilot comments and Cooper-Harper pilot rating were recorded after the evaluation of each configuration. Pilot comments were both tape recorded and noted on the runs logs by one of the

experimenters. Run time history data of relevant parameters were recorded digitally, using on-line data acquisition software, and on analog strip chart recorders.

G. PILOTS

Pilot 1 - Lt Col, USAF. Graduate of the USAF Test Pilot School (TPS). He has 2695 hours of experience in high performance jet fighters and trainers (T-38, F-4, F-15) and 210 in other types of aircraft. Experienced in flying qualities simulations.

Pilot 2 - Major, USAF. Graduate of the French Test Pilot School. Former Flying Qualities Branch Chief of the USAF TPS. He has over 3100 hours of experience in high performance jet fighters and trainers (T-38, F-16, F-106, etc.).

Pilot 3 - Captain, USAF. Graduate of the USAF TPS. He has over 2025 hours of total flying time with 850 hours in high performance jet trainers (T-38) and 990 hours in heavy transports and bombers (KC-135 and B-52).

Pilot 4 - Engineering Test Pilot and experienced flying qualities evaluation pilot. Lecturer on flying qualities at the USAF TPS. Holds fixed-wing single- and multi-engine and helicopter ratings. His flying experience includes over 7500 hours on general aviation aircraft. He has extensive experience on both fixed- and motion-base simulators.

Pilot 5 - Major, USAF. Graduate of the USAF TPS. He has a total of over 3500 hours of flying time including over 2100 hours on high performance jet fighter/attack aircraft (F-16 and A-10). He has over 150 hours of simulation experience.

Pilot 6 - Major, USAF. He has over 2900 hours of total flying experience including over 2480 hours on large transport aircraft (C-5A, C-5B, and C-141) and 240 hours on T-38 jet trainers. Former Flying Qualities Engineer at AFWAL, WPAFB.

Pilot 7 - Captain, USAF. He has 3050 hours of total flying experience including 1250 hours on military trainers and attack aircraft (A-10, A-37, T-38, and T-37) and 1800 hours on general aviation aircraft. No previous exposure to flying qualities evaluations.

H. RESULTS

All the pilot ratings obtained during the experiment are summarized in Tables A-5, A-6, and A-7. The complete simulation run logs are presented in Table A-8 and the transcribed pilot comments are presented in Table A-9.

1. Pilot Ratings

The pilot rating results and associated statistical data for the target acquisition and ground attack tasks for the roll configurations are presented in Tables A-5 and A-6, respectively. The results for the target acquisition task for the pitch configurations (including combined pitch and roll variations) are presented in Table A-7.

The pilot ratings for the target acquisition task by Pilot 6 and those for the ground attack task from Pilot 3 were omitted from the analysis of HQR results in the main text of this report. These ratings are shown flagged in Tables A-5 and A-6. Pilot 6 was a high-time transport pilot who had no previous experience in performing the aggressive gross maneuvers that are typically required during air-combat. He, therefore, had difficulty in achieving the level of aggressiveness necessary to properly evaluate the lateral configurations. In the first two evaluation sessions with this pilot he was able to do the task within the required time but his relatively gentle maneuvering minimized the amount of actuator rate limiting with even the most rate limited configurations, and, therefore, he was not able to discriminate between configurations. In the next evaluation session he attempted to increase and maintain a greater level of aggressiveness but this did not improve his ability to differentiate between configurations and further evaluations using the target acquisition task with this pilot were not pursued. Pilot 6 had no difficulty in learning and performing the ground attack task and was better able to differentiate between configurations using this task.

Pilot 3 had difficulty in learning the ground attack task and adjusting to the relatively unconstrained nature of the task. The evaluations performed by this pilot using this task were all during the initial training period and were not considered valid. Further evaluations with this pilot using the ground attack task were not pursued due to time constraints. The remaining time with this pilot was focused on completing evaluations with the target acquisition and formation flying tasks.

Ratings by Pilot 1 for evaluations using full motion on the LAMARS were also not included in the analysis in the main text. These were excluded to avoid introducing the added variable of motion into the analysis, especially as Pilot 1 commented that the motion seemed inappropriate. Evaluations

TABLE A-5. HQRs AND STATISTICAL DATA FOR THE ROLL CONFIGURATIONS (WITH PITCH CONFIG. P4) USING THE TARGET ACQUISITION TASK

Roll	HQRs for Target Acquisition Task																																
Case	Pilot 1					Pilot 2				Pilot 3						Pilot 4		Pilot 5						Pilot 7					Pilot 6				
1	4	3	2	2	2*	4	2	2		1	3	4	2	3	3	3		3**	3	4.5	2.5			3	4	4	3		4***	5***	4***	2***	
2	3	2				3				3	1					2		2.5**	3	3				4	4	4			4***	3***	4***	4***	2***
3	7	7				8				6	7					7		9**	7					7					6***	7***			
5	3	4				2				1								8**	4**	4				4									
6	7					6	5	4	5	6	6					8		10**	6					7					3***	5***			
7	5	5	5	7*		3	2	3		2	4	6				4		5**	3					5					4***	3***	10***		
8	4	3	3	4*		2	2	2	3	2	3					2		2.5**	2.5**	2				4	4				5***	8***	8***		
9	9					6				8	7							7						5.5									
10	7	5	5			5.5	2			3	6					5		7**	5					5.5					6***				
11	5	4				3	4			3								3**						4.5									
12	10					10				7	9							9						8									
13	6	7				7										.7		4						7									
14	5	4				9	5			7								5.5**						6									
15	10	8	9*			6	6	5		6	7					5.5	5	7**	5.5					7.5					2***	5***	6***		
16	6	5	5	5	7*	2	4	4		3	2	4				3		4.5**	2	4				5					3***	3***	10***		
17	3	3	3*			3	3	2		3								4**	7**	2.5**	3**	2	3	3	5	4.5	3	4	5***	3***	4***		

	Number	AVG	Standard		MAX	MIN
Roll Case	of Samples	HQR	Deviation	Median	HQR	HQR
1	21	2.95	0.91	3.0	4.5	1
2	11	2.91	0.94	3.0	4	1
3	8	7.00	0.53	7.0	8	6
5	6	3.00	1.26	3.5	4	1
6	10	6.00	1.15	6.0	8	4
7	12	3.92	1.31	4.0	6	2
8	13	2.77	0.83	3.0	4	2
9	6	7.08	1.28	7.0	9	5.5
10	10	4.90	1.43	5.0	7	2
11	6	3.92	0.80	4.0	5	3
12	6	8.83	1.17	9.0	10	7
13	6	6.33	1.21	7.0	7	4
14	6	6.00	1.79	5.5	9	4
15	11	6.50	1.52	6.0	10	5
16	14	3.86	1.29	4.0	6	2
17	13	3.19	0.85	3.0	5	2

* Runs flown in the LAMARS with motion (not included in the analysis)
** Runs flown in the LAMARS fixed base (not included in the analysis)
*** Runs not included in the analysis

TABLE A-6. HQRs AND STATISTICAL DATA FOR THE ROLL CONFIGURATIONS (WITH PITCH CONFIG. P4) USING THE GROUND ATTACK TASK

HQRs for Ground Attack Task																
Roll Case	Pilot 1			Pilot 3		Pilot 5			Pilot 6		Number of Samples	AVG HQR	Standard Deviation	Median	MAX HQR	MIN HQR
1	2	4	2*	5**	5**	2			2		4	2.50	1.00	2.0	4	2
2	2			7**	6**	4	2		4		4	3.00	1.15	3.0	4	2
3	7					7			8		3	7.33	0.58	7.0	8	7
5	3										1	3.00		3.0	3	3
6	7	8*		7**		7					2	7.00	0.00	7.0	7	7
7	3	4*		3**	4**	5			4		3	4.00	1.00	4.0	5	3
8	3	3	3*			2.5			3		4	2.88	0.25	3.0	3	2.5
9	8					4.5					2	6.25	2.47	6.3	8	4.5
10	4	5	4	6**		3	2.5	2			6	3.42	1.11	3.5	5	2
11	2*					3			1		2	2.00	1.41	2.0	3	1
12	10					10					2	10.00	0.00	10.0	10	10
13	5					6					2	5.50	0.71	5.5	6	5
14	8					6					2	7.00	1.41	7.0	8	6
15	6	6	9*	7**		4	8		6		5	6.00	1.41	6.0	8	4
16	5	4*		3**		4	3		5		4	4.25	0.96	4.5	5	3
17	3	3*		3**		3			2	2	4	2.50	0.58	2.5	3	2

* Runs flown in the LAMARS with motion (not included in the analysis)

** Runs not included in the analysis

TABLE A-7. HQRs AND STATISTICAL DATA FOR COMBINED PITCH/ROLL CONFIGURATION VARIATIONS USING THE TARGET ACQUISITION TASK

HQRs for Target Acquisition Task (Pitch and Pitch/Roll Variations)																												
Pitch/Roll Case	Pilot 1				Pilot 2				Pilot 3						Pilot 5				Pilot 7				Number of Samples	AVG HQR	Standard Deviation	Median	MAX HQR	MIN HQR
P4/R1	4	3	2	2*	4	2	2		1	3	4	2	3	3	3**	3	4.5	2.5	3	4	4	3	19	3.00	0.93	3.0	4.5	1
P4+80/R1	2	2	5*						3						3		3		3				6	2.67	0.52	3.0	3	2
P4+40/R1	5	4	4*		3				1	2					2.5				4				7	3.07	1.37	3.0	5	1
P4+40/R8					2																		1	2.00		2.0	2	2
P4+20/R1	7	7	9*		2				4	6					4		5		4				8	4.88	1.73	4.5	7	2
P4+20/R8					1																		1	1.00		1.0	1	1
P4+80/R8	3				3				4						2								4	3.00	0.82	3.0	4	2
P4+40/R7	6				3				5	4					5								5	4.60	1.14	5.0	6	3
P4+20/R6	7	7			6	4			7						7								6	6.33	1.21	7.0	7	4
P4+20/R7					3																		1	3.00		3.0	3	3
P4+80/R7															4.5								1	4.50		4.5	4.5	4.5
P3/R1	4	4			4				4										4				5	4.00	0.00	4.0	4	4
P3/R2															5								1	5.00		5.0	5	5

* Runs flown in the LAMARS with motion (not included in the analysis)

** Runs flown in the LAMARS fixed base (not included in the analysis)

performed by Pilot 5 on the LAMARS fixed-base were also excluded from the analysis due to differences in the visual field-of-view between the MS-1 and LAMARS.

In addition to the development of flying qualities boundaries for moderate amplitude maneuvering that is discussed in the main text of this report, a few other "mini-experiments" were performed during this simulation. These are discussed in the following paragraphs.

The effect of motion cues on flying qualities was briefly investigated with Pilot 1. Figure A-14 presents a cross-plot of average HQRs given by Pilot 1 for the ground attack and target acquisition tasks, for fixed- versus moving-base. For the few configurations evaluated on both, HQR's for the rate-limited configurations (configuration identifiers are shown on the plot) tended to be worse on the moving-base simulator. This is true for both the target acquisition and ground attack tasks. Ratings for the unlimited and 80 deg/sec rate limit cases are all within one HQR of the line of perfect agreement, indicating that the addition of motion cues made no discernable difference to the flying qualities of these configurations. Pilot comments indicated that the motion seemed inappropriate for the ground attack task but more appropriate for the target acquisition task, however, the pilot also noted that the motion was not affecting his ratings.

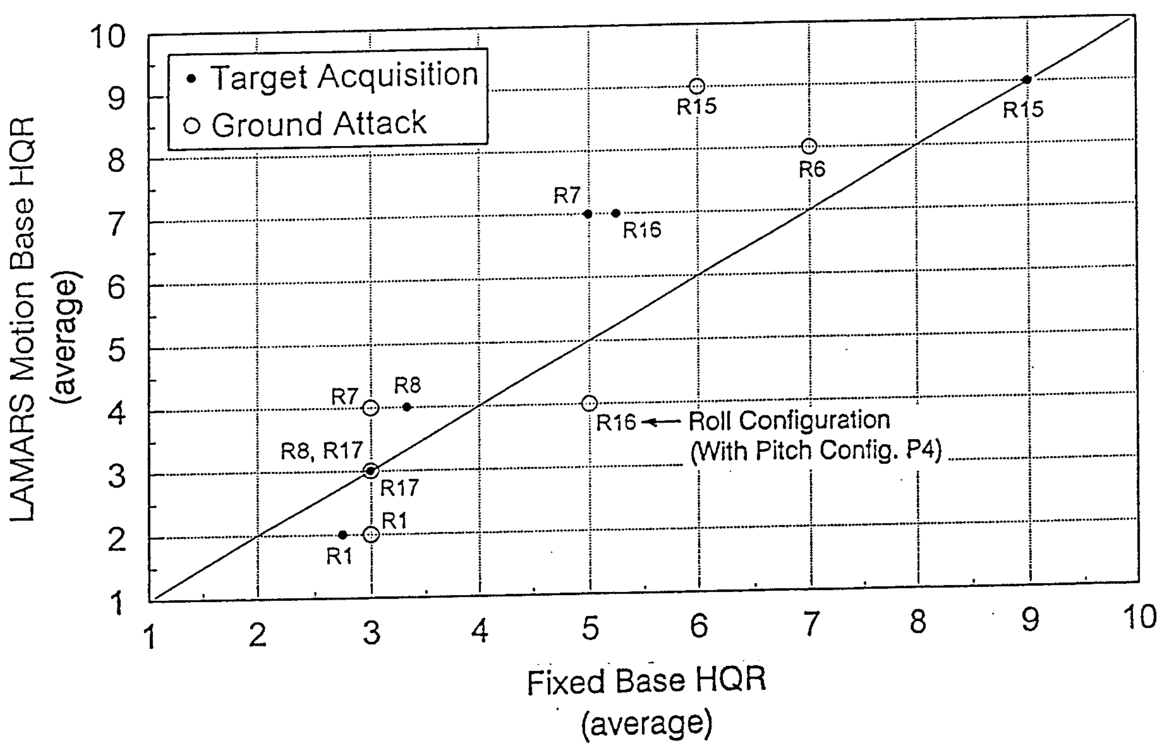


Figure A-14. HQR's for Fixed-Base *vs*. Motion (Pilot 1)

The effect of the roll mode time constant and rate limit on flying qualities is shown in Fig. A-15. Average HQRs for each pilot for each combination of $1/T_R$ and rate limit are shown on the plot. Average HQR for all pilots is also shown for a given configuration. The data shown in Fig. A-15 is for the open-loop configurations with the target acquisition task. This data indicates that for Level 1 flying qualities, a $1/T_R$ of greater than 3 rad/sec and an actuator rate limit of greater than 40 deg/sec is required. Configurations with a 20 deg/sec rate limit were Level 3 or almost Level 3 regardless of the value of $1/T_R$ and the 40 deg/sec rate limit cases were Level 2, also regardless of the value of $1/T_R$. For all values of the actuator rate limit, there is a definite degradation in HQR as $1/T_R$ degrades, indicating that improved roll dynamics could compensate, within limits, for adverse rate limiting.

The effect of multiple degradations in pitch and roll were also investigated briefly. The results of this investigation are presented in Fig. A-16. The pitch and roll configurations were the basic, open-loop configurations in each axis (Configs. P4 and R1) with degradations in the elevator and aileron rate limits. All other parameters were unchanged. Only HQRs for the target acquisition task were considered. Several of these combined configuration evaluations were performed by only one pilot and, therefore, these ratings cannot be weighted heavily in the analysis. In general, the degradation in flying qualities due to elevator rate limiting was not as marked as the degradation due to aileron rate limiting. This may primarily be due to the fact that the task itself was tailored for aggressive lateral maneuvering. This may also be the reason for the considerable disagreement in pilot opinion for these cases.

A high pitch-rate overshoot configuration (Config. P3) was also evaluated. The high pitch-rate configuration was given Level 2 ratings (HQRs of 4) by four pilots. The roll configuration for these evaluations was the ideal roll case (Config. R1). In contrast, the equivalent low pitch-rate overshoot configuration (Config. P4), also in combination with roll Config. R1, was given average Level 1 rating by all the pilots. Pilot comments for Config. P3 indicated that they found the pitch attitude dropback that results from the pitch-rate overshoot to be annoying.

Another "mini-experiment" was the investigation into the effect of rate limiting within a control loop. Configuration pairs R8/R17, R7/R16, and R6/R15, had the same rate limits and the same effective roll dynamics when not on the rate limit. When on the rate limit, however, the augmented cases (Configs. R15, R16, and R17) had degraded roll dynamics as these configurations relied on augmentation to improve the roll dynamics (see Table A-3). Both the individual and average HQRs for these cases (see Table A-5) indicate that there was no appreciable difference in the flying qualities due to the position of the rate limit. This observation is true for both the target acquisition and ground attack tasks. For the configuration pairs

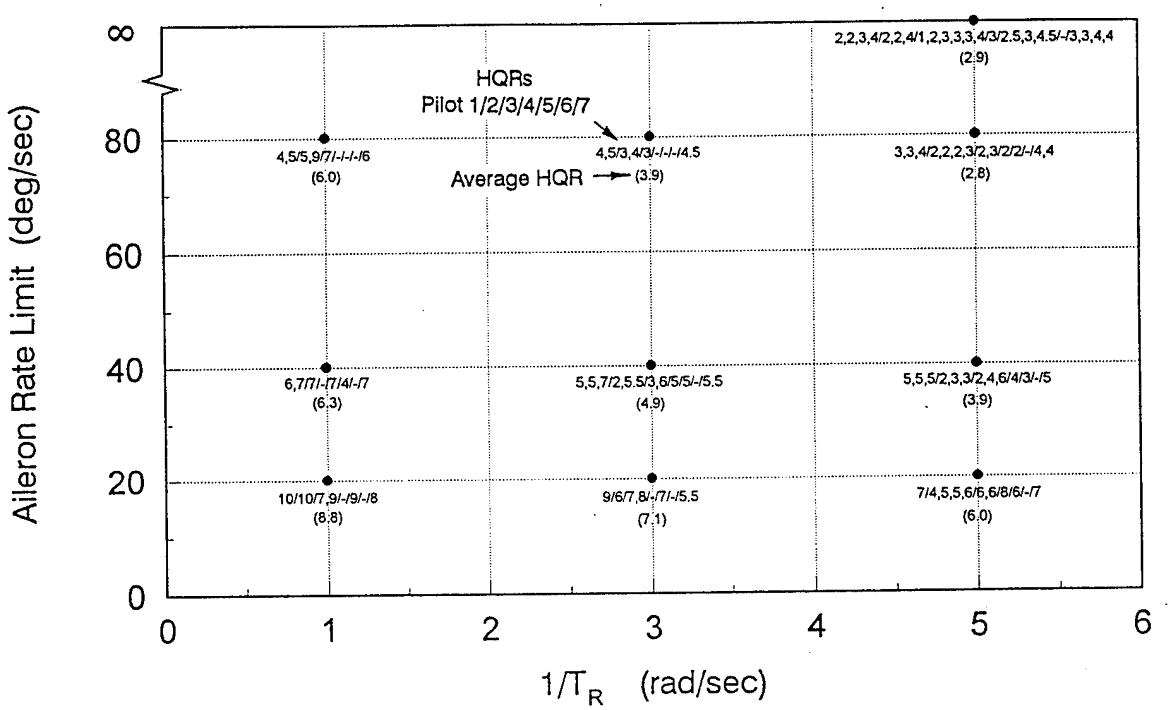


Figure A-15. Effect of $1/T_R$ and Aileron Actuator Rate Limit on HQR
(Target Acquisition Task)

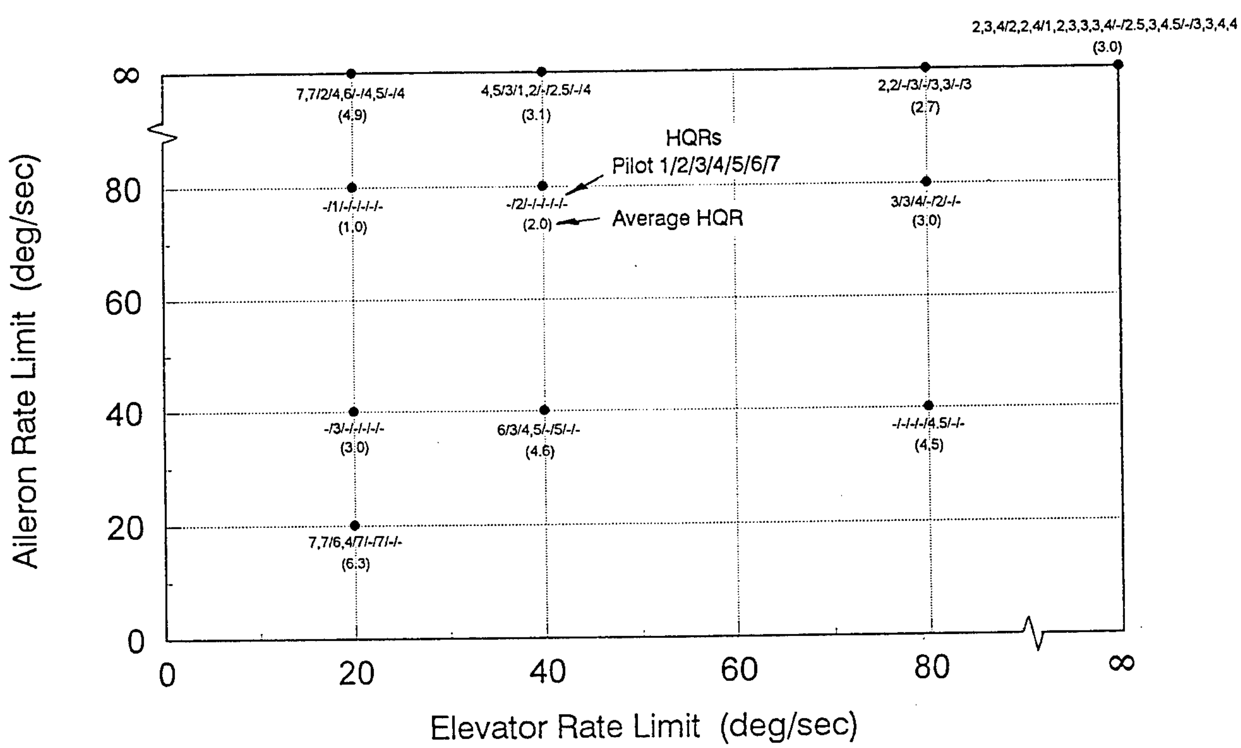


Figure A-16. Effect of Multiple Axis (Pitch/Roll) Degradations in Actuator Rate Limit (Target Acquisition Task)

mentioned above, the average HQRs for the target acquisition task were: 2.8/3.2 for Configs. R8/R17; 3.9/3.9 for Configs. R7/R16; and 6.5/6.0 for Configs. R6/R15.

The results of the limited evaluations using the formation flying/air-refueling task demonstrated a clear pilot preference for the ACAH configuration deemed Level 1 over the RCAH configuration that was deemed Level 2. The pilots found the precision, small amplitude, pitch maneuvering to be easier with the ACAH system.

2. Performance Measurements

The run time history data for the gross maneuvering tasks were surveyed to determine the actual attitude quickness demanded by the pilots during the evaluations. The survey was restricted to the lateral configurations only.

Three surveys were performed. These were:

1. For each configuration with the target acquisition task using the runs for Pilot 1 to examine the effect of configuration on performance. These are presented in Fig. A-17.

2. For Configurations 1 (no rate limit) and 6 (worst rate limit) with Pilots 1, 2, 3, 5, and 7 with the target acquisition task to show pilot-to-pilot variations. These are shown in Figs. A-18 and A-19. The data for Pilot 7, Config. 6 is not shown because the time history data for this run was lost.

3. For Configs. 1 and 6 with Pilots 1 and 5 with the target acquisition and ground attack tasks to show the effect of task on performance. These are presented in Fig. A-20 and A-21.

The attitude quickness was computed using a computer program that computed the $\Delta\phi$ and p_{pk} associated with successive zero-axis crossings of the roll rate signal (p). These calculations were performed during the time segments that the actual acquisition was taking place and not during the periods between targets (see Fig. A-12). As a result of the relatively simple computation method used, several roll maneuvers that are inappropriate for the computation of this parameter (mostly due to small magnitude pilot inputs that do not fully stress the actuator) are included in the plots. These are usually at small values of $\Delta\phi$ (less than 20 deg). In some cases, where the automated routine seemed to be clearly in error, the parameters were re-computed by hand through inspection of the run time history data.

In all these figures, the theoretical maximum attitude quickness line is included as a reference (solid line). Also displayed are the data from cockpit stick pulses performed as a final check of the configurations (open circles). The attitude quickness measurements obtained from the cockpit stick pulses

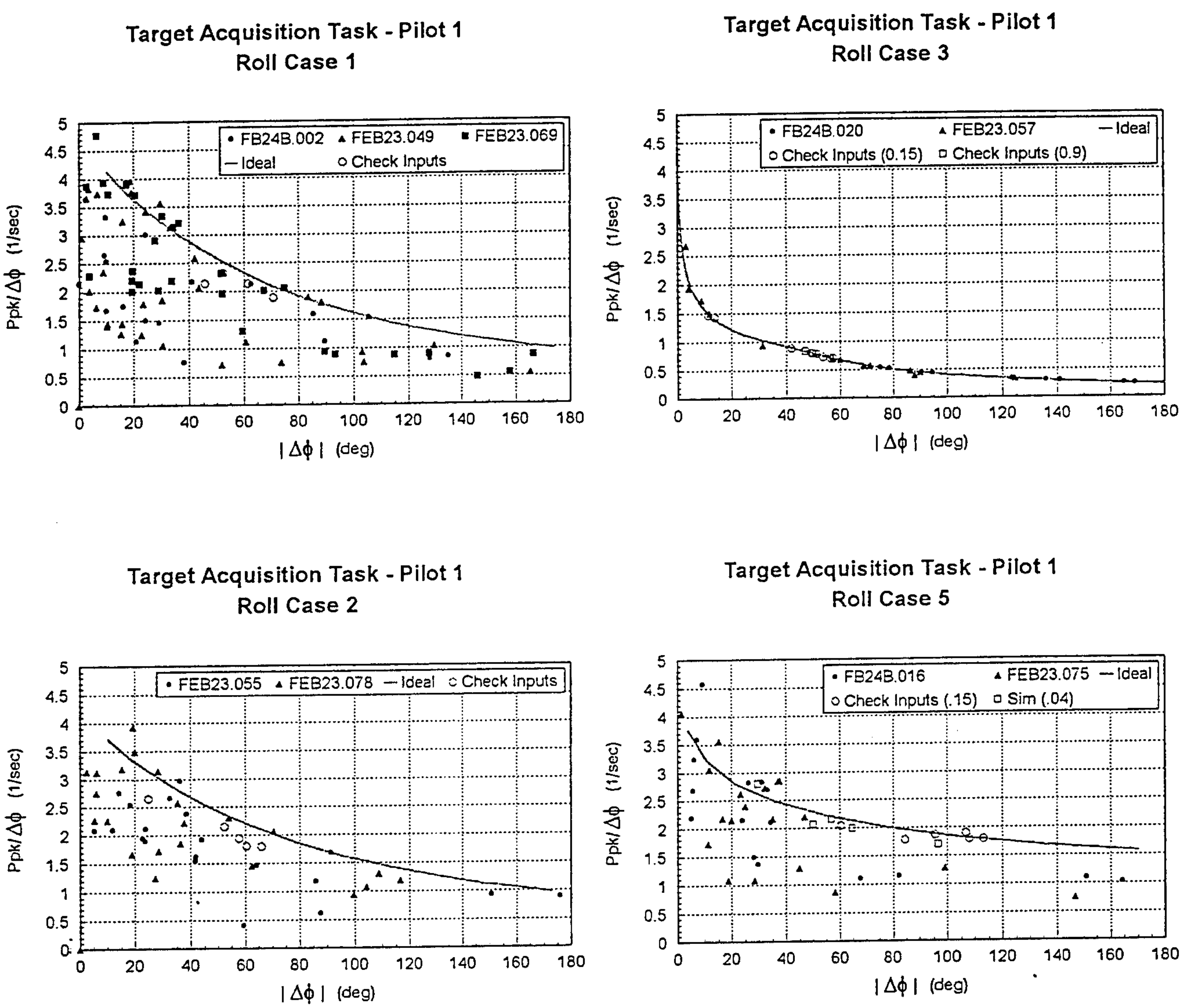
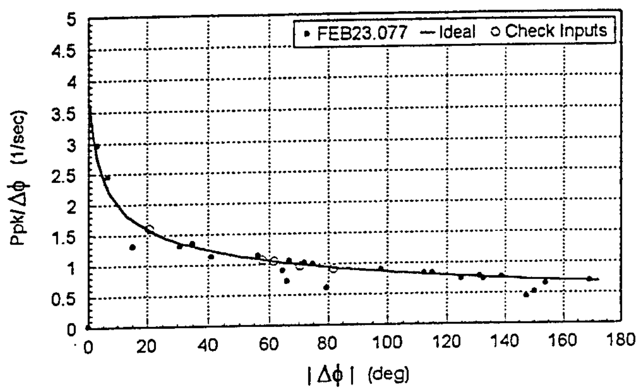
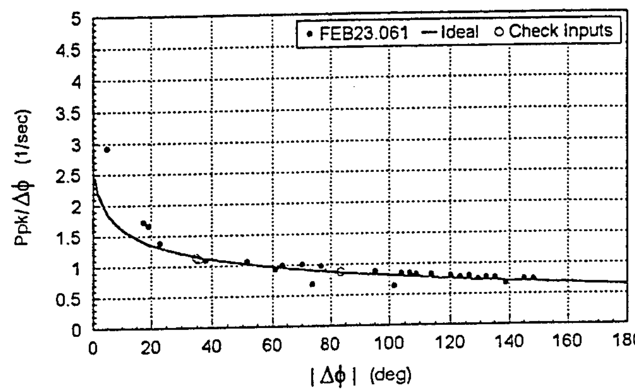


Figure A-17. Achieved Attitude Quickness for Pilot 1, All Configurations (Target Acquisition Task)

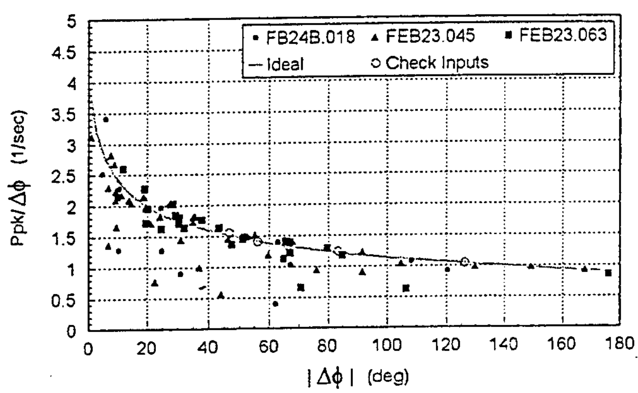
Target Acquisition Task - Pilot 1
Roll Case 6



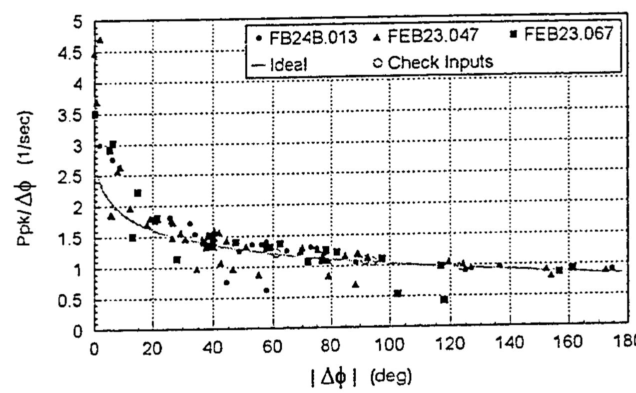
Target Acquisition Task - Pilot 1
Roll Case 9



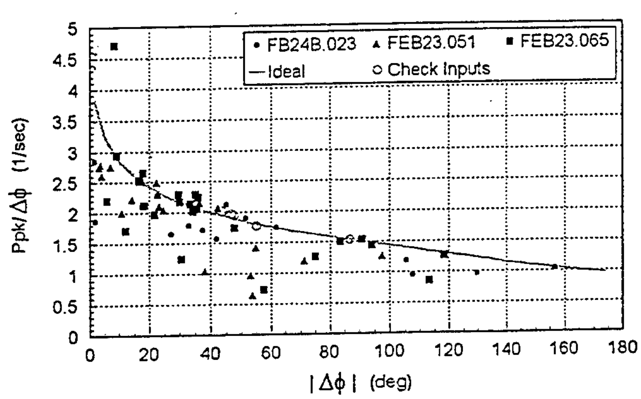
Target Acquisition Task - Pilot 1
Roll Case 7



Target Acquisition Task - Pilot 1
Roll Case 10



Target Acquisition Task - Pilot 1
Roll Case 8



Target Acquisition Task - Pilot 1
Roll Case 11

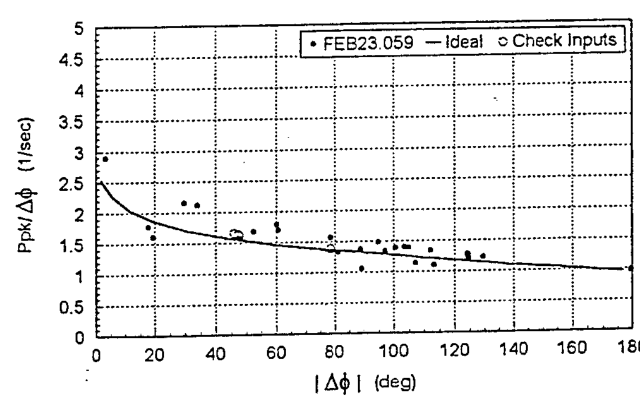
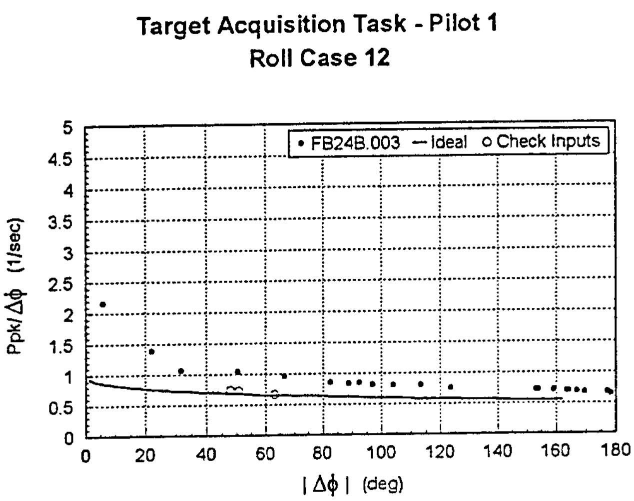
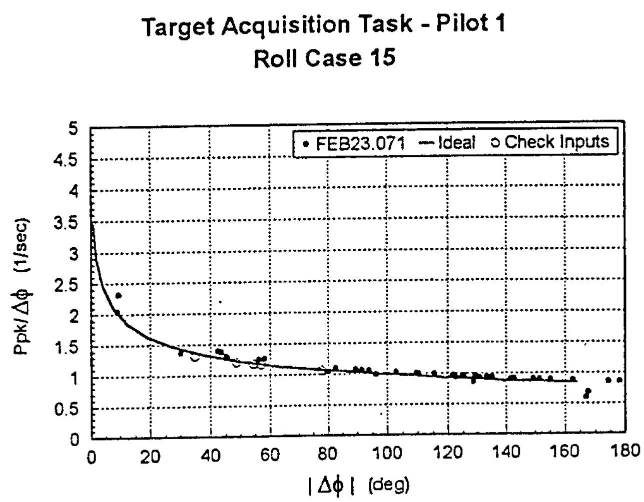
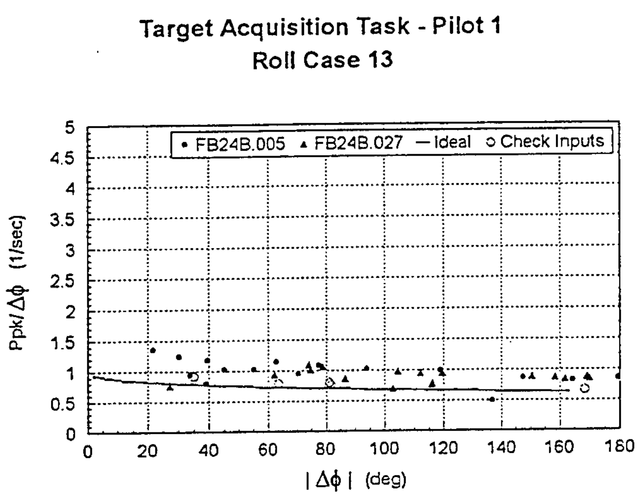
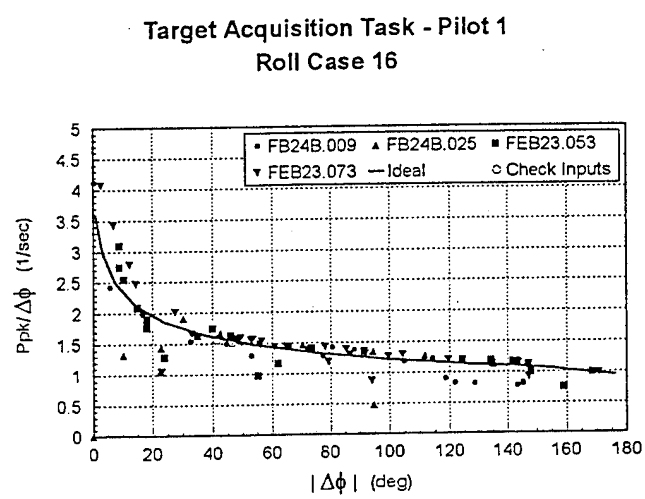


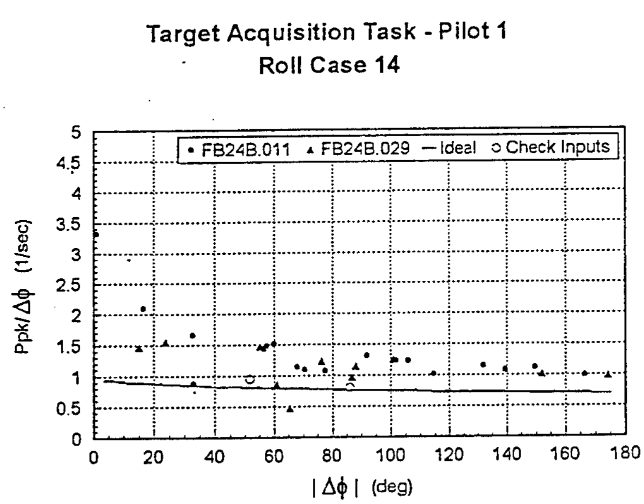
Figure A-17. Achieved Attitude Quickness for Pilot 1, All Configurations (Target Acquisition Task) (continued)











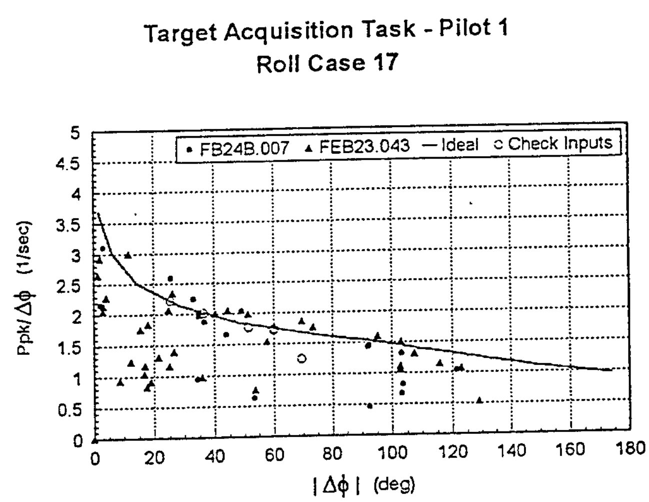


Figure A-17. Achieved Attitude Quickness for Pilot 1, All Configurations (Target Acquisition Task) (concluded)

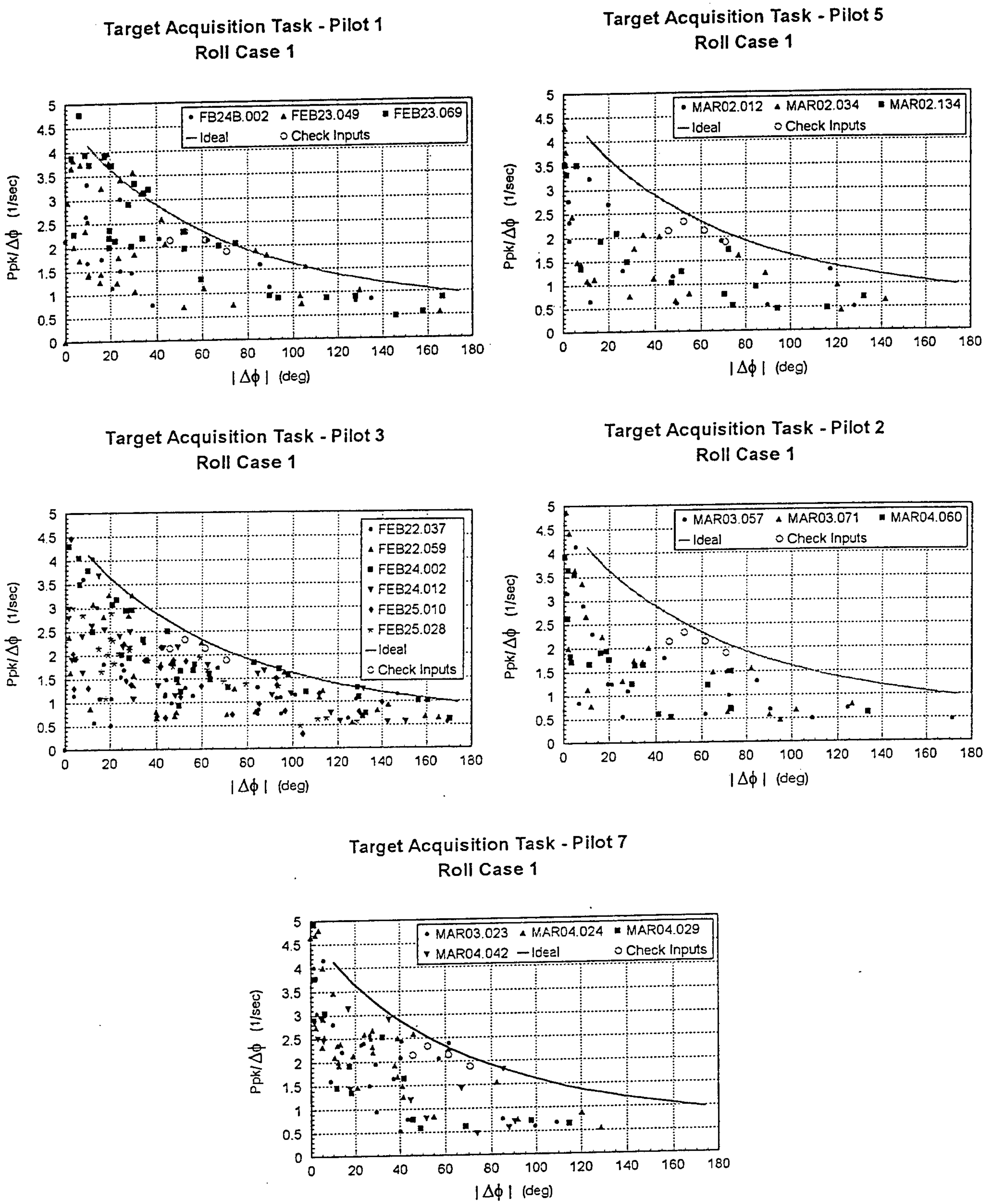


Figure A-18. Achieved Attitude Quickness for Roll Case 1 Pilots 1, 2, 3, 5, and 7 (Target Acquisition Task)

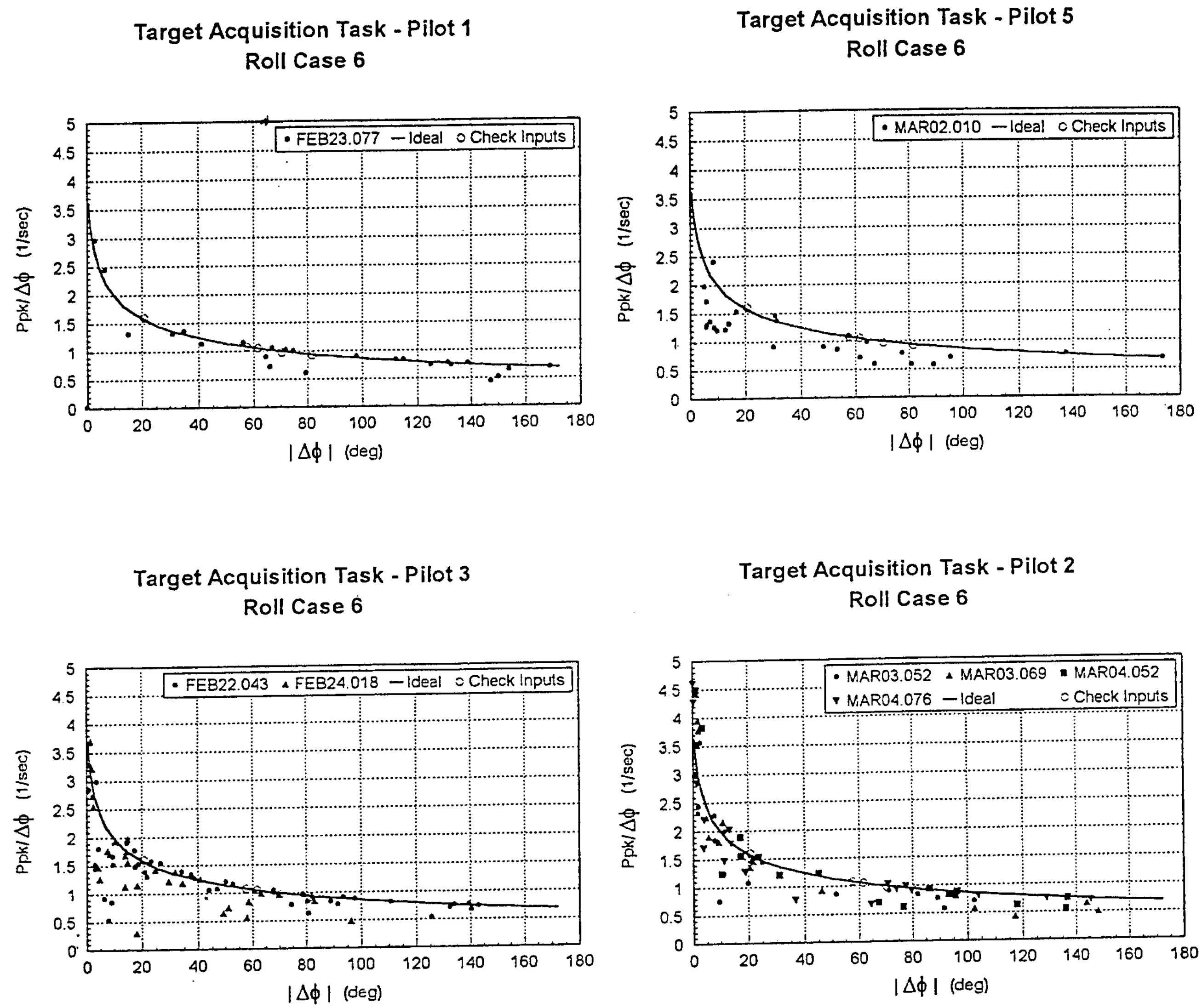


Figure A-19. Achieved Attitude Quickness for Roll Case 6 Pilots 1, 2, 3, and 5 (Target Acquisition Task)

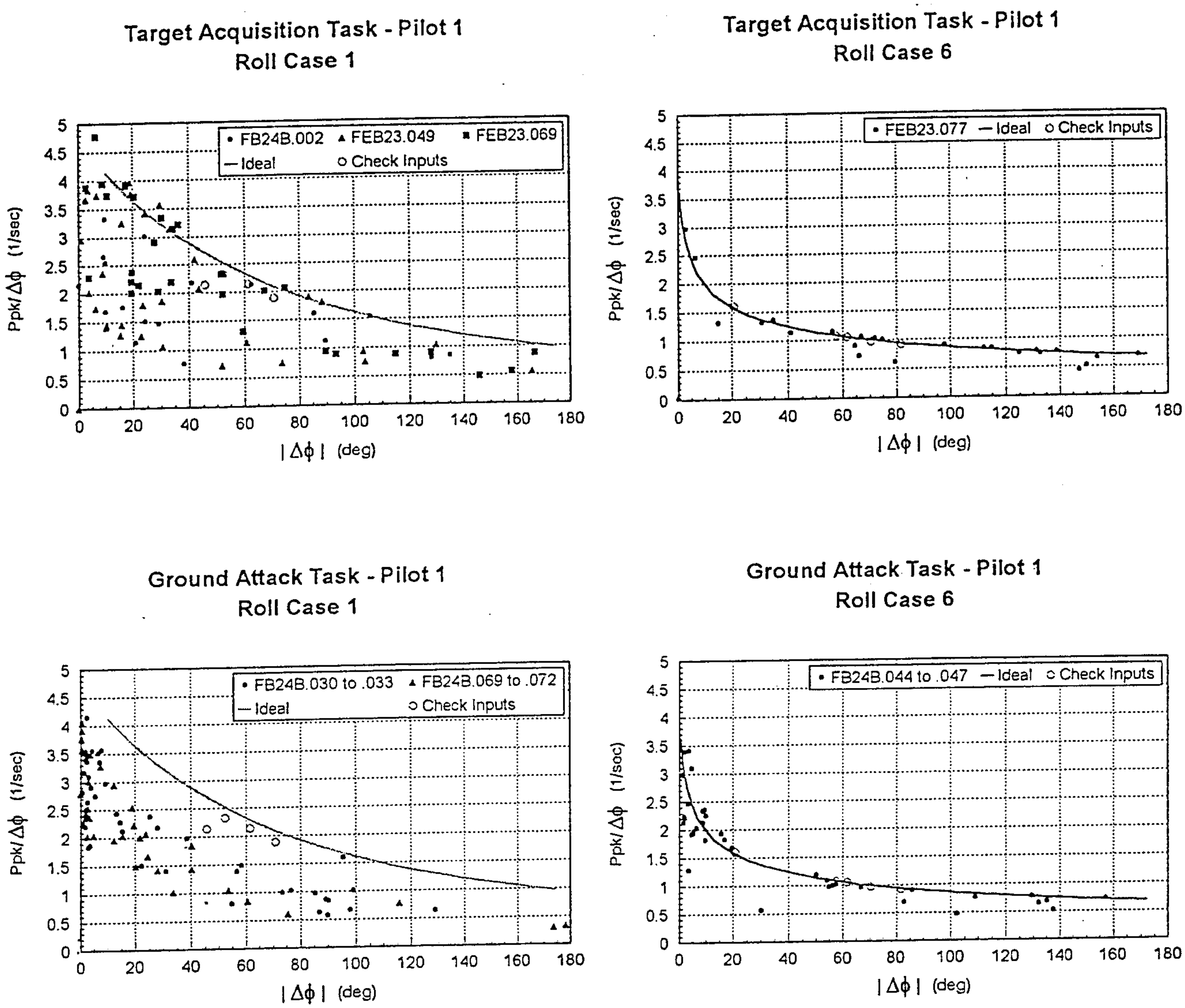


Figure A-20. Achieved Attitude Quickness for Both Tasks for Configurations R1 and R6 (Pilot 1)

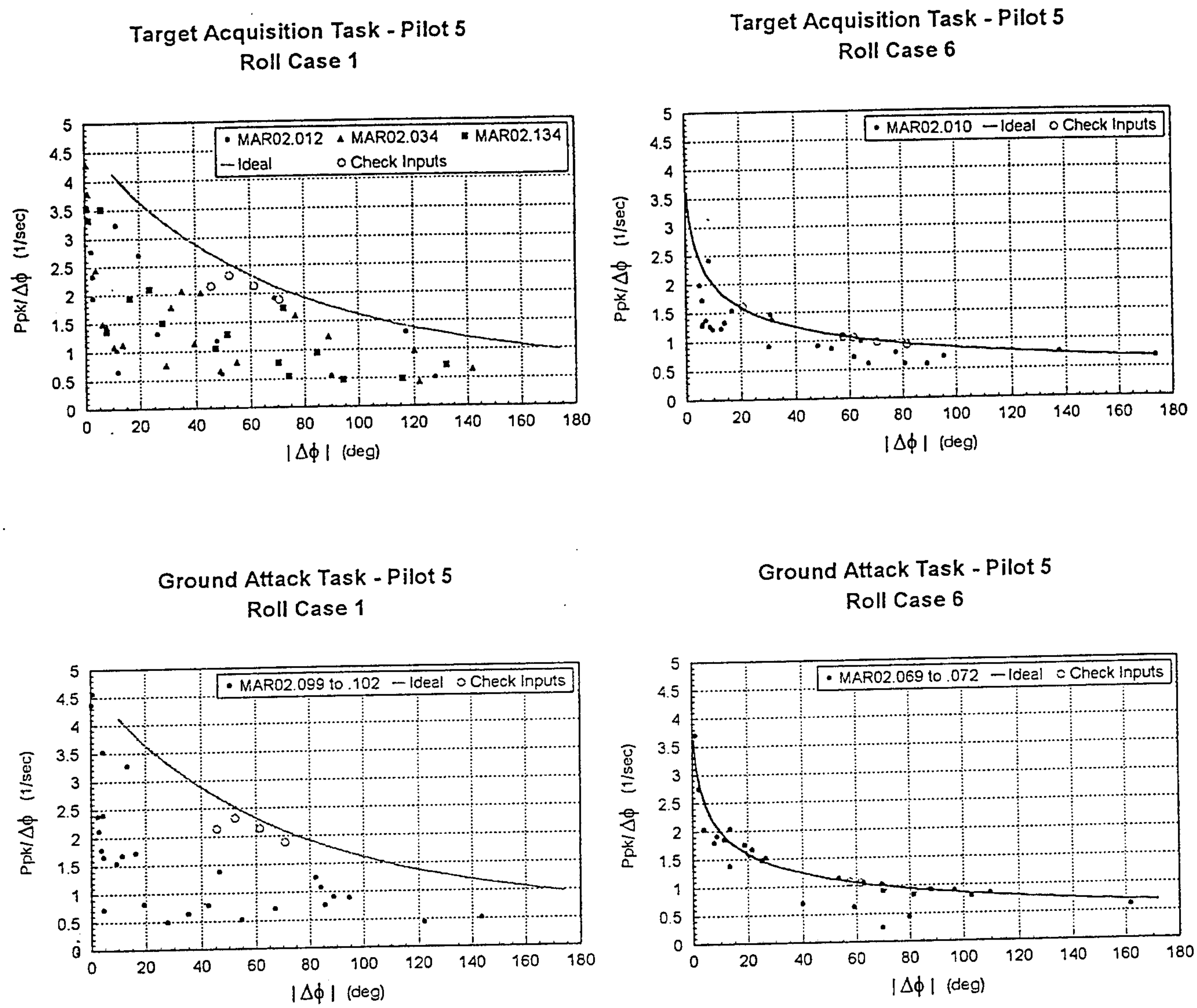


Figure A-21. Achieved Attitude Quickness for Both Tasks for Configurations R1 and R6 (Pilot 5)

closely agree with the theoretical lines indicating that the configurations were simulated accurately and that the effect of the stick dynamics and simulation time delay (not included in the computation of the theoretical line) were negligible.

The results of these surveys are discussed below.

a. Configuration Differences

The demanded roll attitude quickness for all the fixed-base (MS-1) evaluations using the target acquisition task for Pilot 1 are presented in Fig. A-17. In most cases, more than one run was performed for each configuration and these are identified by different symbols on the plots. The run identifiers corresponding to the symbols give the date and run number for each run.

It is clear from Fig. A-17 that Pilot 1 generally used all the available attitude quickness -- the maximum achieved attitude quickness corresponds extremely well with the theoretical maximum line for all configurations except Configs. R11, R12, R13, and R14. In these configurations, the maximum achieved attitude quickness is greater than the theoretical maximum. The reason for this difference is the nature of the pilot input. The criterion and, hence, the theoretical line, assumes an open-loop stick pulse input. With these configurations, all of which have low values of $1/T_R$, the pilot generally cannot control bank angle with the desired precision and aggressiveness using a simple pulse-like input. Instead, he is forced to provide some compensation to adjust for the low value of $1/T_R$. This compensation typically involves the insertion of pilot lead which translates to an initial "overdriving" of the input. As discussed in the main text, this type of control input increases the magnitude of the attitude quickness that can be achieved, at the cost of increased pilot compensation and degraded pilot opinion.

The ability to insert this pilot lead is degraded by the actuator rate limit. This may be observed in the differences between the achieved maximum and the maximum theoretical attitude quickness for Configs. R12, R13, and R14 ($1/T_R = 1$ rad/sec, rate limit of 20, 40, and 80 deg/sec, respectively). As the actuator rate limit decreases in magnitude, the difference between the theoretical and achievable maximum attitude quickness narrows. With the higher $1/T_R$ (3 rad/sec) configurations, the amount of pilot compensation required is less and this difference is smaller in magnitude.

The scatter in the achieved attitude quickness data decreases as the actuator rate limit decreases in magnitude. With the lowest rate limit (20 deg/sec -- Configs. R6, R9, and R15), when $1/T_R$ is favorable, the achieved attitude quickness lies directly on the theoretical maximum line with very little scatter. This is because the pilot is always demanding the maximum performance from the aircraft. With the 40

deg/sec rate-limit (Configs. R7, R10, and 16), the scatter is slightly greater, indicating that the pilot had a little performance reserve for performing the task. With the unlimited rate limit or 80 deg/sec rate limit (Configs. R1, R2, R8, and R17), there is considerable scatter, indicating a considerable performance reserve. These observations indicate that; a 20 deg/sec rate limit is too small to perform this task; a 40 deg/sec rate limit is barely adequate; and a 80 deg/sec rate limit is quite adequate.

Configurations R3 and R5 investigated the effect of increasing control effectiveness with an actuator rate limit. The achieved quickness data for Config. R3 shows that the combination of 40 deg/sec rate limit and low $L_{\delta a}$ does not provide the pilot with sufficient capability to perform the task satisfactorily. The pilot has to always demand the maximum performance from the aircraft (as evidenced by the close correspondence of the theoretical and achieved attitude quickness). When the control effectiveness available is greater, as with Config. R5, the pilot has excess capability and does not need the full capability of the aircraft to perform the task (as evidenced by the differences between the theoretical and achieved attitude quickness).

The achieved attitude quickness data shows no noticeable differences in pilot performance between the closed-loop configurations (R15, R16, and R17) and the equivalent open-loop configurations (R6, R7, and R8). This observation agrees with the pilot rating data that also showed no differences in the positioning of the rate limit.

b. Pilot-to-Pilot Differences

The achieved attitude quickness data for Pilots 1, 2, 3, 5, and 7 are presented in Figs. A-18 (for Config. R1) and A-19 (for Config. R6).

The data for Config. R1 (Fig. A-18) indicates that Pilot 1 was the most aggressive and demanded the maximum performance available more often than the other pilots. Pilots 2 and 5 never demanded the maximum capability. The variation in the demanded attitude quickness (scatter in the data) is similar for all the pilots.

The data for Config. R6 (Fig. A-19) indicates that when faced with a severely rate limited configuration, all pilots generally demanded the maximum capability, in terms of roll attitude quickness, from the aircraft.

c. Task Differences

Figures A-20 and A-21 present the achieved attitude quickness data for Configs. R1 and R6 for Pilots 1 and 5, respectively, for both gross maneuvering tasks.

The data indicates that when not hampered by a rate limit, both pilots required less attitude quickness with the ground-attack task. This is most noticeable for Pilot 1 (Fig. A-20, Config. R1). Both pilots required the maximum available attitude quickness regardless of task, however, in order to perform the tasks, when the roll response is severely rate limited.

REFERENCES

A-1. Mitchell, David G., Bimal L. Aponso, and Roger H. Hoh, *Minimum Flying Qualities, Volume I: Piloted Simulation Evaluation of Multiple Axis Flying Qualities*, WRDC-TR-89-3125, Jan. 1990.

A-2. Whalley, Matthew S., *A Piloted Simulation Investigation of Yaw Attitude Quickness in Hover and Yaw Bandwidth in Forward Flight*, USAAVSCOM TR-92-A-002, Sep. 1992.

TABLE A-8. SIMULATION RUN LOG

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
1 - 2	18-Feb	TA*	P4	R2	-0.075	0.15	P4	2	
3 - 4	18-Feb	TA	P4	R7	-0.075	0.15	P4	4	
5 - 6	18-Feb	TA	P4	R3	-0.075	0.45	P4	7	
7 - 8	18-Feb	TA	P4	R6	-0.075	0.15	P4	8	
9 - 10	18-Feb	TA	P4	R1	-0.075	0.15	P4	3	
11 - 12	18-Feb	TA	P4	R16	-0.075	0.15	P4	3	
13 - 14	18-Feb	TA	P4	R15	-0.075	0.15	P4	5.5	
15 - 16	18-Feb	TA	P4	R8	-0.075	0.15	P4	2	
17 - 18	18-Feb	TA	P4	R10	-0.075	0.15	P4	5	
19 - 20	18-Feb	TA	P4	R13	-0.075	0.15	P4	7	
21 - 22	18-Feb	TA	P4	R15	-0.075	0.15	P4	5	
23 - 24	22-Feb	TA	P4	R2	-0.05	0.15	P6	4	
25 - 27	22-Feb	TA	P4	R7	-0.05	0.15	P6	4	
28 - 30	22-Feb	TA	P4	R3	-0.05	0.6	P6	6	
31 - 32	22-Feb	TA	P4	R6	-0.05	0.15	P6	3	
33 - 35	22-Feb	TA	P4	R1	-0.07	0.15	P6	4	
1 - 3	22-Feb	TA	P4	R16	-0.06	0.15	P6	3	Data stored to Disk 2.
4 - 5	22-Feb	TA	P4	R15	-0.075	0.15	P6	2	
6 - 7	22-Feb	TA	P4	R2	-0.075	0.15	P6	3	
8	22-Feb	TA	P4	R6	-0.075	0.18	P6		Computer crash ended session.
8 - 9	22-Feb	TA	P4	R2	-0.075	0.15	P3	5	Runs 8 through 21 were training runs.
10 - 11	22-Feb	TA	P4	R7	-0.075	0.15	P3	7	
12 - 13	22-Feb	TA	P4	R8	-0.075	0.15	P3	5	
14 - 15	22-Feb	TA	P4	R3	-0.075	0.15	P3	8	
16 - 17	22-Feb	TA	P4	R6	-0.075	0.15	P3	7	
18 - 19	22-Feb	TA	P4	R1	-0.075	0.15	P3	5	
20 - 21	22-Feb	TA	P4	R16	-0.075	0.15	P3	5	
22 - 23	22-Feb	TA	P4	R2	-0.075	0.15	P3	3	Formal evaluations began here.
24 - 25	22-Feb	TA	P4	R15	-0.075	0.15	P3	6	
26 - 27	22-Feb	TA	P4	R7	-0.075	0.15	P3	2	
28 - 29	22-Feb	TA	P4	R10	-0.075	0.15	P3	3	
30 - 31	22-Feb	TA	P4	R8	-0.075	0.15	P3	2	
32 - 33	22-Feb	TA	P4	R9	-0.075	0.15	P3	8	

*TA — Target Acquisition
GA — Ground Attack

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
34 - 35	22-Feb	TA	P4	R16	-0.075	0.15	P3	3	
36 - 37	22-Feb	TA	P4	R1	-0.075	0.15	P3	1	
38 - 39	22-Feb	TA	P4	R12	-0.075	0.15	P3	7	
40 - 41	22-Feb	TA	P4	R7	-0.075	0.15	P3	4	
42 - 43	22-Feb	TA	P4	R6	-0.075	0.15	P3	6	
44 - 45	22-Feb	TA	P4	R2	-0.075	0.15	P3	1	
46 - 47	22-Feb	TA	P4	R16	-0.075	0.15	P3	2	
48 - 49	22-Feb	TA	P4	R3	-0.075	0.15	P3	6	
50 - 51	22-Feb	TA	P4	R8	-0.075	0.15	P3	3	
52 - 53	22-Feb	TA	P4	R10	-0.075	0.15	P3	6	
54 - 55	22-Feb	TA	P4	R12	-0.075	0.15	P3	9	
56 - 57	22-Feb	TA	P4	R15	-0.075	0.15	P3	7	
58 - 59	22-Feb	TA	P4	R1	-0.075	0.15	P3	3	
60 - 61	22-Feb	TA	P4	R9	-0.075	0.15	P3	7	
1 - 2	23-Feb	TA	P4	R2	-0.04	0.15	P6	4	
3 - 5	23-Feb	TA	P4	R7	-0.04	0.15	P6	3	
6 - 7	23-Feb	TA	P4	R15	-0.04	0.12	P6	5	
8 - 10	23-Feb	TA	P4	R1	-0.05	0.15	P6	5	Task time lowered from 15 to 10 seconds.
11 - 13	23-Feb	TA	P4	R6	-0.05	0.13	P6	5	
14 - 16	23-Feb	TA	P4	R16	-0.05	0.13	P6	3	
17 - 19	23-Feb	TA	P4	R15	-0.05	0.13	P6	6	
20 - 21	23-Feb	TA	P4	R8	-0.05	0.13	P6	5	
22 - 24	23-Feb	TA	P4	R10	-0.05	0.13	P6	6	
25 - 26	23-Feb	TA	P4	R3	-0.05	0.4	P6	7	
27 - 29	23-Feb	TA	P4	R2	-0.05	0.14	P6	4	
									Pilot flew formation flying task. No
									formal evaluations. Comments were
									noted.
30 - 31	23-Feb	TA	P4	R1	-0.075	0.1	P1	3	Runs 30 through 41 were training runs.
32 - 33	23-Feb	TA	P4	R7	-0.075	0.15	P1	8	For runs 30 through 49 the task time was
34 - 35	23-Feb	TA	P4	R6	-0.075	0.15	P1	8	approximately 20 seconds. The pilot did
36 - 37	23-Feb	TA	P4	R8	-0.075	0.15	P1	7	not feel that this affected his ratings.
38 - 39	23-Feb	TA	P4	R16	-0.075	0.15	P1	7	

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
40 - 41	23-Feb	TA	P4	R2	-0.075	0.15	P1	4	
42 - 43	23-Feb	TA	P4	R17	-0.075	0.15	P1	3	Formal evaluations began here.
44 - 45	23-Feb	TA	P4	R7	-0.075	0.15	P1	5	
46 - 47	23-Feb	TA	P4	R10	-0.075	0.15	P1	7	
48 - 49	23-Feb	TA	P4	R1	-0.075	0.15	P1	4	
50 - 51	23-Feb	TA	P4	R8	-0.075	0.15	P1	4	Task time was set to 15 seconds.
52 - 53	23-Feb	TA	P4	R16	-0.075	0.15	P1	6	
54 - 55	23-Feb	TA	P4	R2	-0.075	0.15	P1	3	
56 - 57	23-Feb	TA	P4	R3	-0.075	0.3	P1	7	
58 - 59	23-Feb	TA	P4	R11	-0.075	0.15	P1	5	
60 - 61	23-Feb	TA	P4	R9	-0.075	0.15	P1	9	
62 - 63	23-Feb	TA	P4	R7	-0.075	0.15	P1	5	
64 - 65	23-Feb	TA	P4	R8	-0.075	0.15	P1	3	
66 - 67	23-Feb	TA	P4	R10	-0.075	0.15	P1	5	
68 - 69	23-Feb	TA	P4	R1	-0.075	0.15	P1	3	
70 - 71	23-Feb	TA	P4	R15	-0.075	0.15	P1	10	
72 - 73	23-Feb	TA	P4	R16	-0.075	0.15	P1	5	
74 - 75	23-Feb	TA	P4	R5	-0.075	0.04	P1	3	
76 - 77	23-Feb	TA	P4	R6	-0.075	0.15	P1	7	
78	23-Feb	TA	P4	R2	-0.075	0.15	P1	2	
1 - 2	24-Feb	TA	P4	R1	-0.075	0.15	P3	4	
3 - 4	24-Feb	TA	P4	R7	-0.075	0.15	P3	6	
5 - 6	24-Feb	TA	P4	R14	-0.075	0.15	P3	7	
7 - 8	24-Feb	TA	P4	R17	-0.075	0.15	P3	3	
9 - 10	24-Feb	TA	P4	R16	-0.075	0.15	P3	4	
11 - 12	24-Feb	TA	P4	R1	-0.075	0.15	P3	2	
13 - 14	24-Feb	TA	P4	R3	-0.075	0.15	P3	7	
15 - 16	24-Feb	TA	P4	R11	-0.075	0.15	P3	3	
17 - 18	24-Feb	TA	P4	R6	-0.075	0.15	P3	6	
19 - 20	24-Feb	TA	P4	R5	-0.075	0.04	P3	1	Pilot task debrief was recorded.
21 - 24	24-Feb	GA	P4	R1	-0.075	0.15	P3	5	
25 - 28	24-Feb	GA	P4	R7	-0.075	0.15	P3	3	
29 - 32	24-Feb	GA	P4	R10	-0.075	0.15	P3	6	
33 - 36	24-Feb	GA	P4	R2	-0.075	0.15	P3	7	

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
37 - 40	24-Feb	GA	P4	R16	-0.075	0.15	P3	3	
41 - 44	24-Feb	GA	P4	R1	-0.075	0.15	P3	5	
45 - 48	24-Feb	GA	P4	R6	-0.075	0.15	P3	7	
49 - 52	24-Feb	GA	P4	R7	-0.075	0.15	P3	4	
53 - 56	24-Feb	GA	P4	R17	-0.075	0.15	P3	3	
57 - 60	24-Feb	GA	P4	R15	-0.075	0.15	P3	7	
61 - 64	24-Feb	GA	P4	R2	-0.075	0.15	P3	6	
									Pilot flew formation flying task. No formal evaluations. Comments were noted.
1 - 2	24-Feb	TA	P4	R1	-0.075	0.15	P1	2	
3	24-Feb	TA	P4	R12	-0.075	0.15	P1	10	
4 - 5	24-Feb	TA	P4	R13	-0.075	0.15	P1	6	
6 - 7	24-Feb	TA	P4	R17	-0.075	0.15	P1	3	
8 - 9	24-Feb	TA	P4	R16	-0.075	0.15	P1	5	
10 - 11	24-Feb	TA	P4	R14	-0.075	0.15	P1	5	
12 - 13	24-Feb	TA	P4	R10	-0.075	0.2	P1	5	
14 - 16	24-Feb	TA	P4	R5	-0.075	0.04	P1	4	
17 - 18	24-Feb	TA	P4	R7	-0.075	0.15	P1	5	
19 - 20	24-Feb	TA	P4	R3	-0.075	0.9	P1	7	
21 - 23	24-Feb	TA	P4	R8	-0.075	0.15	P1	3	
24 - 25	24-Feb	TA	P4	R16	-0.075	0.15	P1	5	
26 - 27	24-Feb	TA	P4	R13	-0.075	0.15	P1	7	
28 - 29	24-Feb	TA	P4	R14	-0.075	0.15	P1	4	
30 - 33	24-Feb	GA	P4	R1	-0.075	0.15	P1	2	
34 - 38	24-Feb	GA	P4	R7	-0.075	0.15	P1	3	
39 - 43	24-Feb	GA	P4	R10	-0.075	0.15	P1	4	
44 - 47	24-Feb	GA	P4	R6	-0.075	0.15	P1	7	
48 - 52	24-Feb	GA	P4	R16	-0.075	0.15	P1	5	
53 - 56	24-Feb	GA	P4	R2	-0.075	0.15	P1	2	
57 - 60	24-Feb	GA	P4	R3	-0.075	0.15	P1	7	
61 - 65	24-Feb	GA	P4	R15	-0.075	0.15	P1	6	
66 - 72	24-Feb	GA	P4	R1	-0.075	0.15	P1	4	
73 - 79	24-Feb	GA	P4	R10	-0.075	0.15	P1	5	

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
80 - 83	24-Feb	GA	P4	R9	-0.075	0.15	P1	8	
									Pilot flew formation flying task. No
									formal evaluations. Comments were
									noted.
1-8	25-Feb	GA	P4	R1	-0.075	0.15	P3	Not Rated	Pilot did not formally evaluate the GA
9 - 10	25-Feb	TA	P4	R1	-0.075	0.15	P3	3	task. However, extensive comments
11 - 12	25-Feb	TA	P4+20	R1	-0.075	0.15	P3	4	were recorded.
13 - 14	25-Feb	TA	P4+40	R1	-0.075	0.15	P3	1	
15 - 16	25-Feb	TA	P4+80	R8	-0.075	0.15	P3	4	
17 - 18	25-Feb	TA	P4+40	R7	-0.075	0.15	P3	5	
19 - 20	25-Feb	TA	P4+20	R6	-0.075	0.15	P3	7	
21 - 22	25-Feb	TA	P4+80	R1	-0.075	0.15	P3	3	
23 - 24	25-Feb	TA	P3	R1	-0.075	0.15	P3	4	
25 - 26	25-Feb	TA	P4+20	R1	-0.075	0.15	P3	6	
27 - 28	25-Feb	TA	P4	R1	-0.075	0.15	P3	3	
29 - 30	25-Feb	TA	P4+40	R1	-0.075	0.15	P3	2	
31 - 32	25-Feb	TA	P4+40	R7	-0.075	0.15	P3	4	
33 - 34	25-Feb	TA	P4	R1	-0.075	0.15	P1	2	
35 - 36	25-Feb	TA	P4+40	R1	-0.075	0.15	P1	5	
37 - 38	25-Feb	TA	P4	R15	-0.075	0.15	P1	8	
39 - 40	25-Feb	TA	P4+20	R1	-0.075	0.15	P1	7	
41 - 43	25-Feb	TA	P4+80	R8	-0.075	0.15	P1	3	
44 - 45	25-Feb	TA	P4+40	R7	-0.075	0.15	P1	6	
46 - 47	25-Feb	TA	P3	R1	-0.075	0.15	P1	4	
48 - 49	25-Feb	TA	P4+20	R6	-0.075	0.15	P1	7	
50 - 51	25-Feb	TA	P4+80	R1	-0.075	0.15	P1	2	
52 - 54	25-Feb	TA	P4+40	R1	-0.075	0.15	P1	4	
55 - 56	25-Feb	TA	P4	R11	-0.075	0.15	P1	4	
57 - 58	25-Feb	TA	P4+20	R1	-0.08	0.15	P1	7	
59 - 60	25-Feb	TA	P3	R1	-0.075	0.15	P1	4	
61 - 62	25-Feb	TA	P4+20	R6	-0.075	0.15	P1	7	
63 - 64	25-Feb	TA	P4+80	R1	-0.075	0.15	P1	2	
65 - 68	25-Feb	GA	P4	R8	-0.075	0.15	P1	3	

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
69 - 72	25-Feb	GA	P4	R14	-0.075	0.15	P1	8	
73 - 76	25-Feb	GA	P4	R12	-0.075	0.15	P1	10	
77 - 80	25-Feb	GA	P4	R5	-0.075	0.05	P1	3	
81 - 84	25-Feb	GA	P4	R10	-0.075	0.15	P1	4	
85 - 88	25-Feb	GA	P4	R17	-0.075	0.15	P1	3	
89 - 92	25-Feb	GA	P4	R13	-0.075	0.15	P1	5	
93 - 97	25-Feb	GA	P4	R16	-0.075	0.15	P1	4	
98 - 102	25-Feb	GA	P4	R8	-0.075	0.15	P1	3	
103 - 107	25-Feb	GA	P4	R15	-0.075	0.15	P1	6	
1 - 2	28-Feb	TA	P4	R2	-0.075	0.15	P6	2	
3 - 5	28-Feb	TA	P4	R17	-0.075	0.15	P6	5	
6 - 8	28-Feb	TA	P4	R1	-0.075	0.15	P6	4	
9 - 10	28-Feb	TA	P4	R16	-0.075	0.15	P6	10	
11 - 13	28-Feb	TA	P4	R17	-0.075	0.15	P6	3	
14 - 15	28-Feb	TA	P4	R8	-0.075	0.15	P6	8	
16 - 17	28-Feb	TA	P4	R1	-0.075	0.17	P6	2	
18 - 19	28-Feb	TA	P4	R8	-0.075	0.17	P6	8	
20 - 21	28-Feb	TA	P4	R7	-0.075	0.15	P6	10	
22 - 24	28-Feb	TA	P4	R17	-0.075	0.15	P6	4	
25 - 27	28-Feb	GA	P4	R1	-0.075	0.15	P1	2	
28 - 31	28-Feb	GA	P4	R17	-0.075	0.15	P1	3	Tasks were flown in the LAMARS with
32 - 35	28-Feb	GA	P4	R16	-0.075	0.15	P1	4	motion on.
36 - 41	28-Feb	GA	P4	R8	-0.075	0.15	P1	3	
42 - 45	28-Feb	GA	P4	R7	-0.075	0.15	P1	4	
46 - 49	28-Feb	GA	P4	R6	-0.075	0.15	P1	8	
50 - 54	28-Feb	GA	P4	R11	-0.075	0.15	P1	2	
55 - 58	28-Feb	GA	P4	R15	-0.075	0.15	P1	9	
59 - 63	28-Feb	GA	P4+40	R1	-0.075	0.15	P1	2	
1A - 3A	28-Feb	TA	P4	R1	-0.075	0.15	P1	2	
4A - 6A	28-Feb	TA	P4	R17	-0.075	0.15	P1	3	
7A - 8A	28-Feb	TA	P4	R16	-0.075	0.15	P1	7	
9A - 11A	28-Feb	TA	P4	R8	-0.075	0.15	P1	4	
12A	28-Feb	TA	P4	R15	-0.075	0.15	P1	9	

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
13A - 14A	28-Feb	TA	P4	R7	-0.075	0.15	P1	7	
15A - 17A	28-Feb	TA	P4+40	R1	-0.075	0.15	P1	4	
18A - 19A	28-Feb	TA	P4+20	R1	-0.075	0.15	P1	9	
20A - 22A	28-Feb	TA	P4+80	R1	-0.075	0.15	P1	5	
1 - 5	1-Mar	GA	P4	R1	-0.075	0.15	P6	2	Tasks were flown fixed base in the
6 - 11	1-Mar	GA	P4	R17	-0.075	0.15	P6	2	LAMARS.
12 - 17	1-Mar	GA	P4	R8	-0.075	0.15	P6	3	
18 - 23	1-Mar	GA	P4	R7	-0.075	0.15	P6	4	
24 - 27	1-Mar	GA	P4	R16	-0.075	0.15	P6	5	
28 - 33	1-Mar	GA	P4	R2	-0.075	0.15	P6	4	
34 - 40	1-Mar	GA	P4	R15	-0.075	0.15	P6	6	
41 - 45	1-Mar	GA	P4	R17	-0.075	0.15	P6	2	
46 - 49	1-Mar	GA	P4	R3	-0.075	0.15	P6	8	
50 - 54	1-Mar	GA	P4	R11	-0.075	0.15	P6	1	
1B - 2B	1-Mar	TA	P4	R1	-0.075	0.15	P5	3	Tasks were flown fixed base in the
3B - 5B	1-Mar	TA	P4	R17	-0.075	0.15	P5	4	LAMARS.
6B - 7B	1-Mar	TA	P4	R8	-0.075	0.15	P5	2.5	
8B - 10B	1-Mar	TA	P4	R7	-0.075	0.15	P5	5	
11B - 13B	1-Mar	TA	P4	R16	-0.075	0.15	P5	4.5	
14B - 15B	1-Mar	TA	P4	R2	-0.075	0.15	P5	2.5	
16B - 18B	1-Mar	TA	P4	R15	-0.075	0.15	P5	7	
19B - 21B	1-Mar	TA	P4	R17	-0.075	0.15	P5	7	
22B - 24B	1-Mar	TA	P4	R6	-0.075	0.15	P5	10	
25B - 26B	1-Mar	TA	P4	R8	-0.075	0.15	P5	2.5	
27B - 28B	1-Mar	TA	P4	R17	-0.075	0.15	P5	2.5	
29B - 30B	1-Mar	TA	P4	R11	-0.075	0.15	P5	3	
31B - 32B	1-Mar	TA	P4	R14	-0.075	0.15	P5	5.5	
33B	1-Mar	TA	P4	R14	-0.075	0.15	P5		Repeated by mistake.
34B - 35B	1-Mar	TA	P4	R5	-0.075	0.15	P5	8	
36B - 37B	1-Mar	TA	P4	R3	-0.075	0.15	P5	9	
38B - 39B	1-Mar	TA	P4	R5	-0.075	0.04	P5	4	
40B - 41B	1-Mar	TA	P4	R17	-0.075	0.15	P5	3	
42B - 44B	1-Mar	TA	P4	R10	-0.075	0.15	P5	7	

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
45B	1-Mar	TA	P4	R6	-0.075	0.15	P5	9	This rating should be discounted.
1 - 2	2-Mar	TA	P4	R2	-0.08	0.2	P5	3	
3 - 4	2-Mar	TA	P4	R17	-0.08	0.15	P5	2	
5 - 6	2-Mar	TA	P4	R8	-0.08	0.15	P5	2	
7 - 8	2-Mar	TA	P4	R7	-0.08	0.15	P5	3	
9 - 10	2-Mar	TA	P4	R6	-0.08	0.15	P5	6	
11 - 12	2-Mar	TA	P4	R1	-0.08	0.15	P5	3	
13 - 15	2-Mar	TA	P4	R16	-0.08	0.15	P5	2	
16 - 17	2-Mar	TA	P4	R15	-0.08	0.15	P5	5.5	
18 - 20	2-Mar	TA	P4	R5	-0.08	0.15	P5	4	
21 - 22	2-Mar	TA	P4	R3	-0.08	0.6	P5	7	
23 - 24	2-Mar	TA	P4	R10	-0.08	0.15	P5	5	
25 - 26	2-Mar	TA	P4	R9	-0.08	0.15	P5	7	
27 - 28	2-Mar	TA	P4	R16	-0.08	0.15	P5	4	
29 - 30	2-Mar	TA	P4	R13	-0.08	0.1	P5	4	
31	2-Mar	TA	P4	R12	-0.08	0.15	P5	9	
32 - 34	2-Mar	TA	P4	R1	-0.08	0.15	P5	4.5	
37 - 40	2-Mar	GA	P4	R2	-0.08	0.15	P5	4	
41 - 46	2-Mar	GA	P4	R17	-0.08	0.15	P5	3	
47 - 50	2-Mar	GA	P4	R16	-0.08	0.15	P5	4	
51 - 55	2-Mar	GA	P4	R15	-0.08	0.15	P5	4	
56 - 60	2-Mar	GA	P4	R8	-0.08	0.15	P5	2.5	
61 - 67	2-Mar	GA	P4	R7	-0.08	0.15	P5	5	
68 - 72	2-Mar	GA	P4	R6	-0.08	0.15	P5	7	
73 - 76	2-Mar	GA	P4	R10	-0.08	0.15	P5	3	
77 - 81	2-Mar	GA	P4	R11	-0.08	0.15	P5	3	
82 - 85	2-Mar	GA	P4	R14	-0.08	0.15	P5	6	
86 - 89	2-Mar	GA	P4	R13	-0.08	0.15	P5	6	
90 - 93	2-Mar	GA	P4	R12	-0.08	0.15	P5	10	
94 - 98	2-Mar	GA	P4	R10	-0.08	0.15	P5	2.5	
99 - 102	2-Mar	GA	P4	R1	-0.08	0.15	P5	2.5	
103 - 107	2-Mar	GA	P4	R16	-0.08	0.15	P5	3	
108 - 113	2-Mar	GA	P4	R15	-0.08	0.15	P5	8	
114 - 117	2-Mar	GA	P4	R9	-0.08	0.15	P5	4.5	

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
118 - 121	2-Mar	GA	P4	R10	-0.08	0.15	P5	2	
122 - 125	2-Mar	GA	P4	R3	-0.08	0.15	P5	7	
126 - 130	2-Mar	GA	P4	R2	-0.08	0.15	P5	2	
131 - 132	2-Mar	TA	P4	R17	-0.075	0.15	P5	3	
133 - 134	2-Mar	TA	P4	R1	-0.075	0.15	P5	2.5	
135 - 136	2-Mar	TA	P4+80	R1	-0.075	0.15	P5	3	
137 - 138	2-Mar	TA	P4+40	R1	-0.075	0.15	P5	2.5	
139 - 140	2-Mar	TA	P4+20	R1	-0.075	0.15	P5	4	
141 - 142	2-Mar	TA	P4+80	R8	-0.075	0.15	P5	2	
143 - 144	2-Mar	TA	P4+80	R1	-0.075	0.15	P5	3	
145 - 146	2-Mar	TA	P4+80	R7	-0.075	0.15	P5	4.5	
147 - 148	2-Mar	TA	P4+40	R7	-0.075	0.15	P5	5	
149 - 150	2-Mar	TA	P4+20	R6	-0.075	0.15	P5	7	
151 - 152	2-Mar	TA	P4	R2	-0.075	0.15	P5	3	
153 - 154	2-Mar	TA	P3	R2	-0.075	0.15	P5	5	
155 - 156	2-Mar	TA	P4+20	R1	-0.075	0.15	P5	5	
									Pilot flew formation flying task. No
									formal evaluations. Comments were
									noted.
2 - 4	3-Mar	TA	P4	R2	-0.075	0.15	P7	4	
5 - 7	3-Mar	TA	P4	R17	-0.075	0.15	P7	3	
8 - 11	3-Mar	TA	P4	R8	-0.075	0.15	P7	4	
12 - 13	3-Mar	TA	P4	R16	-0.075	0.15	P7	5	
14 - 16	3-Mar	TA	P4	R15	-0.075	0.15	P7	7.5	
17 - 20	3-Mar	TA	P4	R11	-0.075	0.15	P7	4.5	
21 - 23	3-Mar	TA	P4	R1	-0.075	0.15	P7	3	
24 - 26	3-Mar	TA	P4	R8	-0.075	0.15	P7	4	
27 - 28	3-Mar	TA	P4	R7	-0.075	0.15	P7	5	
29 - 31	3-Mar	TA	P4	R6	-0.075	0.15	P7	7	
32 - 34	3-Mar	TA	P4	R2	-0.075	0.15	P7	4	
35 - 37	3-Mar	TA	P4	R10	-0.075	0.15	P7	5.5	
38 - 39	3-Mar	TA	P4	R2	-0.075	0.15	P2	3	
40 - 41	3-Mar	TA	P4	R17	-0.075	0.15	P2	3	

TABLE A-8. SIMULATION RUN LOG (continued)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
42 - 43	3-Mar	TA	P4	R8	-0.075	0.15	P2	2	
45 - 46	3-Mar	TA	P4	R7	-0.075	0.15	P2	3	
47 - 48	3-Mar	TA	P4	R16	-0.075	0.15	P2	2	
49 - 50	3-Mar	TA	P4	R11	-0.075	0.15	P2	3	
51 - 52	3-Mar	TA	P4	R6	-0.075	0.15	P2	6	Task time lowered from 15 to 10 seconds.
53 - 55	3-Mar	TA	P4	R16	-0.075	0.15	P2	4	
56 - 57	3-Mar	TA	P4	R1	-0.075	0.15	P2	4	
58 - 59	3-Mar	TA	P4	R8	-0.075	0.15	P2	2	
60 - 61	3-Mar	TA	P4	R15	-0.075	0.15	P2	6	
62 - 63	3-Mar	TA	P4	R7	-0.075	0.15	P2	2	
64 - 65	3-Mar	TA	P4	R10	-0.075	0.15	P2	5.5	
66 - 67	3-Mar	TA	P4	R14	-0.075	0.15	P2	9	
68 - 69	3-Mar	TA	P4	R6	-0.075	0.15	P2	5	Task time returned to 15 seconds.
70 - 71	3-Mar	TA	P4	R1	-0.075	0.15	P2	2	
72 - 73	3-Mar	TA	P4	R8	-0.075	0.15	P2	2	
74 - 76	3-Mar	TA	P4	R15	-0.075	0.15	P2	6	
77 - 78	3-Mar	TA	P4	R7	-0.075	0.15	P2	3	
79 - 80	3-Mar	TA	P4	R10	-0.075	0.15	P2	2	
81 - 82	3-Mar	TA	P4	R14	-0.075	0.15	P2	5	
83 - 84	3-Mar	TA	P4	R16	-0.075	0.15	P2	4	
85 - 86	3-Mar	TA	P4	R17	-0.075	0.15	P2	3	
87 - 88	3-Mar	TA	P4	R13	-0.075	0.15	P2	7	
89 - 90	3-Mar	TA	P4	R12	-0.075	0.15	P2	10	
91 - 92	3-Mar	TA	P4	R11	-0.075	0.15	P2	4	
93 - 94	3-Mar	TA	P4	R9	-0.075	0.15	P2	6	
1 - 3	4-Mar	TA	P4	R2	-0.075	0.15	P7	4	
4 - 5	4-Mar	TA	P4	R17	-0.075	0.15	P7	5	
6 - 7	4-Mar	TA	P4	R14	-0.075	0.15	P7	6	
8 - 10	4-Mar	TA	P4	R13	-0.075	0.15	P7	7	
11 - 12	4-Mar	TA	P4	R12	-0.075	0.15	P7	8	
13 - 15	4-Mar	TA	P4	R17	-0.075	0.15	P7	4.5	
16 - 17	4-Mar	TA	P4	R5	-0.075	0.05	P7	4	
18 - 20	4-Mar	TA	P4	R9	-0.075	0.9	P7	5.5	
21 - 22	4-Mar	TA	P4	R3	-0.075	0.15	P7	7	

TABLE A-8. SIMULATION RUN LOG (concluded)

			Configuration		Stick Gains				
Run #	Date	Task	Longitudinal	Lateral	Kse	Ksa	Pilot ID	HQR	Remarks
23 - 24	4-Mar	TA	P4	R1	-0.075	0.15	P7	4	
25 - 26	4-Mar	TA	P4	R17	-0.075	0.15	P7	3	
27 - 29	4-Mar	TA	P4	R1	-0.075	0.15	P7	4	
30 - 31	4-Mar	TA	P4	R17	-0.075	0.15	P7	4	
32 - 33	4-Mar	TA	P4+80	R1	-0.075	0.15	P7	3	
34 - 37	4-Mar	TA	P4+40	R1	-0.075	0.15	P7	4	
38 - 40	4-Mar	TA	P4+20	R1	-0.075	0.15	P7	4	
41 - 42	4-Mar	TA	P4	R1	-0.075	0.15	P7	3	
43 - 44	4-Mar	TA	P3	R1	-0.075	0.15	P7	4	
45 - 46	4-Mar	TA	P4	R17	-0.075	0.15	P2	2	
47 - 48	4-Mar	TA	P4	R8	-0.075	0.15	P2	3	
49 - 50	4-Mar	TA	P4	R15	-0.075	0.15	P2	5	
51 - 52	4-Mar	TA	P4	R6	-0.075	0.15	P2	4	
53 - 54	4-Mar	TA	P4	R5	-0.075	0.15	P2	2	
55 - 56	4-Mar	TA	P4	R3	-0.075	0.15	P2	8	
57 - 58	4-Mar	TA	P3	R1	-0.075	0.15	P2	4	
59 - 60	4-Mar	TA	P4	R1	-0.075	0.15	P2	2	
61 - 62	4-Mar	TA	P4+40	R1	-0.075	0.15	P2	3	
63 - 64	4-Mar	TA	P4+40	R7	-0.075	0.15	P2	3	
65 - 66	4-Mar	TA	P4+20	R1	-0.075	0.15	P2	2	
67 - 68	4-Mar	TA	P4+20	R6	-0.075	0.15	P2	6	
									Pilot flew formation flying task. No
									formal evaluations. Comments were
									noted.
69 - 70	4-Mar	TA	P4+80	R8	-0.075	0.15	P2	3	
71 - 72	4-Mar	TA	P4+40	R8	-0.075	0.15	P2	2	
73 - 74	4-Mar	TA	P4+20	R8	-0.075	0.15	P2	1	
75 - 76	4-Mar	TA	P4	R6	-0.075	0.15	P2	5	
77 - 78	4-Mar	TA	P4+20	R6	-0.075	0.15	P2	4	
79 - 80	4-Mar	TA	P4+20	R7	-0.075	0.15	P2	3	

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity)

Date: 18 Feb. 1994; Pilot 4

Runs 1 & 2; P4/R2; HQR 2: Roll control on this configuration is excellent, it is extremely predictable, essentially no tendency to bobble, PIO or overshoot the target. Not a lot to say about it, because it is pretty close to ideal case. HQR 2.

Runs 3 & 4; P4/R7; HQR 4: Pretty much satisfactory, except on the targets that were further off the centerline. There was some tendency to overshoot just a little bit. So it felt kind of like a momentary change in the way it flew if I was very aggressive with it. It was only in the extremely aggressive maneuvering that expose some problems so in that case that would be the only deficiency. Once I was out of that region at the end of the highly aggressive capture maneuver, fine tracking was fine. I got satisfactory performance. Desired performance requires moderate pilot compensation. Due to those momentary cases where I tended to overbank in the aggressive 90° bank and capture cases. HQR 4.

Runs 5 & 6; P4/R3; HQR 7: This one apparently seemed to be or qualitatively seemed to be low on roll rate. I just couldn't seem to generate the rates and it was sluggish, ponderous would be a good description of it. Required a lot of lead. I would have to get the roll back in and then try to get it out quickly, so I couldn't just get the good crisp rapid response you need to do this task. Deficiencies do require improvement as opposed to warranted. Numerous times when I climbed out and didn't get the target. Major deficiency is too sluggish. HQR 7.

Runs 7 & 8; P4/R6; HQR 8: This one has a strong tendency for lateral pilot induced oscillations. Any attempt to be aggressive resulted in lateral PIO. It wasn't sustained PIO, it certainly was lateral oscillations in trying to keep the target in the pipper which strongly affected the ability to do the task. It was very unpredictable. Any tightening up caused overshoots. In some cases the target timed out and in some cases I did get the target it was only luck that I was in the middle of an oscillation. HQR 8, because there is compensation even to maintain control, by here I don't mean loss of control in a crash, but control to do the task.

Runs 9 & 10; P4/R1; HQR 3: Was close to ideal, very little tendency to bobble at all in roll, in fact none. Maybe very slight tendency for some minor roll bobbling, but it was definitely minor. Very predictable. And I am sort of torn a little bit between a 2 and a 3. There are a few cases where I notice a slight roll oscillation. But all in all it seems pretty much like the first one that I flew. Because of that a slight tendency which might of been me or the airplane I am not sure, I will call it a HQR 3. Mildly unpleasant deficiencies. Very slight tendency for a roll bobble, but it could of easily been a 2. Not sure about that.

Runs 11 & 12; P4/R1; HQR 3: Flying qualities on that for most part seem really good, and the only one I had any trouble with, was one of those that is far off to the side, way off to the left, had a little overshooting there, but I think that was more me than it was the airplane. Even there I finally did get the target even though I had a couple of bobbles that actually caused it to overshoot, but that was only one out of 12 times. It is probably satisfactory without improvement. In fact in most cases I was able to keep the target inside the small circle. Mildly unpleasant deficiencies because of that one case where I was kind of little behind the airplane. I wasn't sure if it was me or the flying qualities. HQR 3.

Runs 13 & 14; P4/R15; HQR 5.5: On that one, this configuration would be marginal satisfactory somewhere like a 3 or 4, but for the one or two cases where there was a large lateral displacement the configuration was not acceptable. I got into some moderate roll oscillations in trying to get to the target before I timed out. Deficiencies warrant improvement. Mainly for those cases where the airplane requires much more aggressive large angle capture. For those case the deficiencies were somewhere between moderately and very objectionable, tend to overbank got into a good lateral oscillation and timed out before getting it. Between a 5 and 6 if I had to give it a whole rating be a 5 or 5½ is the rating.

Runs 15 & 16; P4/R8; HQR 2: I think this configuration is ideal for this task, very crisp very predictable. Is it satisfactory without improvement? definitely. Negligible deficiencies, really no compensation. I just let go of the stick when I want to stop rolling and it stops. Very low compensation. HQR 2.

Runs 17 & 18; P4/R10; HQR 5: Configuration tended to be easy to start the roll, but a little bit of a problem in stopping it where you wanted it, especially for cases where I got a little behind the action and needed to be aggressive to do your correction and there I got in kind of a nasty roll oscillation. That only happened in a few cases. I think after 12 runs probably 10 where the desired was reached, maybe 2 in the adequate, but those two resulted in fairly significant roll oscillations and some of the desired cases also resulted in roll oscillations. While most of the performances were desired the workload I think were more than moderately objectionable because you can't tease it. As soon as you get aggressive it bites back. Moderately objectionable for those cases I talked about. HQR 5.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 19 & 20; P4/R13; HQR 7: Configuration was one of those that's easy to get the roll started, but very difficult to get stopped where you want it and any tendency to be aggressive results in substantial roll oscillations. I learned early during the practice to back off, and to be very gentle with it, and lead it and pay a lot of attention to it especially in stopping the roll. So I think I got adequate or desired performance in all the cases, however, just one of those cases where I think the performance doesn't really drive the aggressiveness. It doesn't really indicate the quality of the configuration. I don't think it was acceptable. I think it requires improvement. Any lapse in attention and tightening up in the controls can easily result in severe oscillations, in fact when I was practicing I tried to do a 90° roll and ended up inverted. I think the deficiencies are significant enough to require rather than warrant improvement Its major. Controllability was not a question for the task. HQR 7, even though the performance was probably desired. In fact some of those desired cases I was on the verge of losing it and I just happened to get it before I lost it.

Runs 21 & 22; P4/R15; HQR 5: Again with this configuration I got desired performance on every one but the very last case. I am not sure if I shot it down or timed out, but there was a moderately strong tendency to be in a roll oscillation for cases where I had an aggressive capture maneuver. That is definitely degrading for that configuration, it required me to back out of the loop. I think in terms of getting ratings on these probably desirable should mean on the end that if we capture the target with minimal roll oscillations, there are tendency with opening bank angle oscillations so you will be able to capture it and stabilize in roll with very low tendency for residual oscillations. In that context this was definitely not desired, even though the other performance metrics were. Deficiencies warrant improvement. Moderately objectionable. And again a tendency for oscillations. HQR 5.

<u>Date: 27 Feb. 1994; Pilot 6</u>

Runs 23 & 24; P4/R2; HQR 4:

Both runs were very controllable, adequate performance was attainable with very easy pilot workload. Didn't have a whole lot of trouble at all acquiring the target or homing in on the target, most of the waffling around I felt was my own mistakes in overshooting etc., in trying to correct those was most of my problems. They were self induced. It wasn't anything that I could sense in the airplane itself. Is it satisfactory without improvement? no. Deficiencies do warrant improvement, but I would concentrate primarily on a little bit of sensitivity when I am trying to get a real fine smooth lock on the target, in other words the ability to stop a transition of the target across the target zone. I had a little bit of trouble doing that to the point where I would say it was moderately objectionable to the point to where I noticed it. Adequate performance requires, I wouldn't say considerable pilot compensation, but I would say moderate pilot compensation, because I noticed myself allowing for that especially in the larger offsets the ones where I really have to go get them either high, low or sideways it got worse. So that is why I would give it a 4.

Runs 25, 26 & 27; P4/R7; HQR 4: The configuration is controllable. Adequate performance is attainable with a tolerable pilot workload. Meaning adequate performance I think I got kills on all 6 targets if I remember correctly. Is it satisfactory without improvement? no. Deficiencies that warrant improvement is minor but annoying deficiencies. Desired performance requires moderate pilot compensation. The moderate however, is not as bad as the last time. I had to make a little bit of allowance for it but this is a better configuration for tracking and it was easier to line things up. I found myself trying to be smoother on acquiring the target aggressively. You can still improve but I don't know if it is good enough to say fair but mildly unpleasant deficiencies I still noticed it, this is why I say a 4.

Runs 28, 29 & 30; P4/R3; HQR 6: I didn't attain adequate performance. Twice I ran out of time but I still think that it is attainable with adequate workload. Very objectionable but tolerable deficiencies. Adequate performance requires extensive pilot compensation. I wanted a third run to verify that particularly, especially on the wider offsets, I found my self collaborating myself using the old —well it looks like about time to roll out-type techniques or just a offset which every way it went the more aggressive the worse it was and it definitely needs something, "what ever something is," but the ability to recover from large offsets is not very good at all and therefore the tracking task is hindered. I would say 6.

Runs 31 & 32; P4/R6; HQR 3: On both of those runs the configuration is definitely controllable. Some mildly unpleasant deficiencies. Minimal pilot compensation required for desired performance. I think the overshoots were basically mild aggressiveness. The second run was to get to the point. I was tying to avoid treating it too much like a pinball game, understand what I am saying, in other words not like these simulators you see at the pinball shows, but treating it like a real airplane and it just had a minor tendency to go a little bit to far. So minimal pilot compensation to get rid of the problem is what crossed

my mind and it was very easy, much easier than the previous configuration to perform the tracking task. Once I made that compensation, even on the large offsets, it was easy to acquire and then settle out and track the target. Basically I had no problems. HQR 3.

Runs 33, 34 & 35; P4/R1; HQR 4: Note on these runs you gave it a HQR 4. The main point was that the more aggressive I went after the larger overshoots the harder it was to pull in behind the target. I went through a couple of the targets just passed right through them and then reacquired. The more aggressive it is, the harder it is, but if I put a longer lead time in there and started pulling things out earlier, the corrections I did to go after the targets became very easy that is why a 4.

Disk 2 Runs 1, 2 & 3; P4/R16; HQR 3: All three runs were definitely controllable. Adequate performance is attainable with a tolerable pilot workload. Is it satisfactory without improvement? yes. Mildly unpleasant deficiencies. Minimal pilot compensation required for desired performance. In fact minimal pilot compensation required for more than desired performance. Slight tendency for some oscillations once you are trying to hone in on the target. It is easy to avoid overshooting, and by overshooting I didn't mean overshooting in the sense that you described it to me earlier, but I mean overshooting the target itself. So I am not bouncing around with the sight and the circles on the screen, so for those reasons I give it a 3. HQR 3.

Disk 2 Runs 4 & 5; P4/R15; HQR 2: Negligible deficiencies. Pilot compensation not a factor for desired performance. It was easy tracking, stopping. I really had to get into it to even start anything close to a pitch and a roll oscillation so I give it a 2. Very good for the tracking task.

Disk 2 Runs 6 & 7; P4/R2; HQR 3: I had to get into eliminating pitch, particularly oscillations, a little more actively than with the last configuration. This one I noticed a tendency, the more aggressive I got the easier it was to get into an oscillation type of thing. I went through a couple of the acquiring, I just went right through the target and had to come right back and get it. Fine tuning at the end was a little bit difficult, more difficult than it has been. It was to the point to where I had to physically or mentally prepare myself to make a little lead toward pulling out the correction. I had to start an acquisition type of a task. For that reason I give it a 3. HQR 3.

<u>Date: 22 Feb. 1994; Pilot 3</u>

Disk 2 Data Runs 8 & 9; P4/R2; HQR 5: Overall comments on the stick seem very sensitive in pitch although as soon as you relax and not necessarily drive it the other way, the pitch stopped or the motion stopped. A little less sensitive in roll. It took me a bit to get it going. A little bit to get it to stop. So heavy the roll rate once you got it going then it was kind of hard to stop the roll rate right on the button, so it was not very precise. It seemed to have a coupling problem or something when I was chasing both in pitch and roll. The roll seemed very hard to track. The pitch seemed easier to track when I coupled it up with the roll I don't know if that makes much sense. There is pretty much gross acquisition and it was probably very difficult for most of them. Once I can get it into the circle, I came off the controls and almost relaxed a little bit in order to fine track. Moderately objectionable deficiencies. Because I did have to use considerable pilot compensation. My workload was pretty good to get it where I wanted it. So it was definitely a 5.

Disk 2 Runs 10 & 11; P4/R7; HQR 7: Comments overall the more aggressive you got with this one the more oscillations you seem to get into. It would overshoot quite consistently. Pitch was hard to tell I would definitely say the roll too, because I saw a couple of pure roll I just couldn't keep it on, couldn't get back and forth. So it seemed really easy to overshoot the target. The more aggressive I got the easier it is when I just laid off the stick, relaxed, got out of the loop, it was a lot easier to track both gross and fine. Gross acquisition when it was aggressive was very difficult. Fine tracking was a little easier as long as the target was not moving as much. Is it controllable? yes. I didn't achieve adequate performance with a tolerable workload so I would say deficiencies do require improvement. There was some adequate performances not attainable with maximum tolerable pilot compensation. Controllability is not questioned. I don't think you have a problem with controllability. The airplane was controllable. So I would say it was definitely a 7. HQR 7.

Disk 2 Runs 12 & 13; P4/R8; HQR 5: Overall the pitch seemed really good. I could almost put it where I wanted to with hardly any bobbling. The roll though, I couldn't get it to roll fast enough for me. It seem real slow. It was very difficult to reverse the roll, it seemed like I didn't oscillate too much once I got around the target. I had a tendency to overshoot the target a little bit trying to get to it. Is it controllable? yes. I did achieve adequate performance on the first one and I think on the second one and it is not satisfactory without improvement. I seemed to relax a little bit in the pitch and tried to lead the roll a

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

little bit. I tried to really get on watching the wing tips of the airplane get way ahead of the roll. I have to say I definitely used some compensation, and I would say it was considerable pilot compensation not extensive, but just considerable, so a 5.

Disk 2 Runs 14 & 15; P4/R3; HQR 8: Slow roll rate. Very slow response in roll. Slow response in pitch also, but not as slow as it was in roll. It was excessive. Unusable for the mission. Is it controllable? yes. Is adequate performance attainable with a tolerable pilot workload? no. I would say a major deficiencies to do the job here. Intense pilot compensation is required to retain control? no, but considerable pilot compensation is required for control of the airplane. Not necessary to retain control. Control is not really a factor here but to do the job it requires considerable pilot compensation. It is an 8. HQR 8.

Disk 2 Runs 16 & 17; P4/R6; HQR 7: Overall comments it seemed like for the roll you would get it where you want it and it would just continue. I developed an easy PIO in roll, pitch was pretty good, but the roll was definitely really hard to control. I would have to say when I relaxed on it, I did a little better. There are major deficiencies. Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question. That's the one I could control the airplane if I relaxed on it, I didn't try to get too aggressive so I would say a 7.

Disk Runs 18 & 19; P4/R1; HQR 5: Pitch seems very nice you could easily track it to where you wanted. The roll seems a little slow behind the airplane in front of it. I couldn't get it quite where I wanted to. I didn't notice a whole lot of oscillation tendencies. There was just one or two where I would overshoot when I got too aggressive. Is it controllable? yes. Adequate performance was attainable the tolerable pilot workload and it is not satisfactory without improvement and deficiencies warrant improvement mostly in the roll. Adequate performance requires considerable pilot compensation. Desired performance requires moderate pilot compensation. Give it a 5 because there were some moderately objectionable deficiencies I can't name them though but it was there.

Disk 2 Runs 20 & 21; P4/R16; HQR 5: I would have to say that the roll almost seemed like it rolled around on the point and it was very difficult to pull and roll together where the roll did not translate at all. It was like a point roll. It was difficult to get the airplane rolled and pulled together to where you wanted it. The roll rate seemed pretty good and it stayed up sometimes and I had to lead it a little bit. And it wasn't a PIO, it was pretty well damped. It was controllable. There were some annoying deficiencies because I could only attain it adequate, and I would say it requires considerable pilot compensation. HQR 5.

Disk 2 Runs 22 & 23; P4/R2; HQR 3: Overall comments the aircraft seemed to roll right away when I wanted it, stopped pretty much right when I wanted, without waffling at all. I could pull it right to a point, didn't have too much problems, didn't have a tendency to over control or under control. Overall it seemed like a fairly good system. It is satisfactory? I did hit desired on the last one not on the first one. It is not a rachet, it is almost like as soon as I release the pressure on the roll it stops. There is some negligible deficiencies. Minimal pilot compensation is required for desired performance. HQR 3.

Disk 2 Runs 24, & 25; P4/R15; HQR 6: It seemed to roll at a pretty good rate, it didn't want to stop real easy. I couldn't roll out right where I wanted it to, it wanted to continue a little bit wobble around down there, almost like it wanted to wobble in roll. Otherwise it started to roll a little slow and then picked it up pretty quick, and then it wouldn't stop the roll. By relaxing and not asking too much roll right in the beginning and slowly moving the stick with it and I got what I wanted. I would have to say the deficiencies were objectionable, and it required extensive, anytime I have to get out of the loop that much to fly it, its extensive compensation to relax that one. HQR 6.

Disk 2 Runs 26 & 27; P4/R7; HQR 2: Overall very nice. Seems responsive in the roll exactly how I would like it. It stopped rolling where I wanted to, it didn't pick up too fast making me overshoot it like crazy, didn't waffle around without making me sick to my stomach. I would buy that system. Pilot compensation is not a factor for desired performance, really there wasn't much pilot compensation if any. So I would say it is between a 1 and 2. And the reason I would give it a negligible deficiencies it seemed to be just a couple little pinpointing deficiencies and I had a hard time pointing a couple times in fine tracking. But that was not part of the task. HQR 2.

Disk 2 Runs 28 & 29; P4/R10; HQR 3: Overall it was a fairly good system. The roll rate seemed to be a little slower, a little harder to command. When I wanted to get it there and pinpoint it and pull it across it bust out at the end, so I would command the roll over there, but once I got it there, it got there fairly quickly. It just didn't want to pick up, get me right there, so I missed the crispness. That is the best way to describe it. It didn't seem crisp, it seemed a little sloppy in the roll. I just could not command exactly want I wanted. Minimal pilot compensation required for desired performance. HQR 3.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Disk 2 Runs 30 & 31; P4/R8; HQR 2: Overall I really liked the crispness on that one. It got me where I wanted to go, it seemed to be very responsive, it rolled nice and quick, it got me right there. I didn't have a hard time chasing around. I felt like I didn't have to stay a step and a half ahead of the other airplane. I could try to catch up to him when he did something. The only thing I could think of that I used compensation on was, I did tone down my aggressiveness just a little bit, but I found out when I raised my aggressiveness back up, the system performed better. I would have to say it is between a 1 and 2. It is number 2 because nothing is perfect.

Disk 2 Runs 32 & 33; P4/R9; HQR 8: Overall it seemed like it is very slow to pick up the roll that I commanded. It didn't want to pick it up, but then once it got going it wouldn't stop, so I over shot the roll back and forth. Pitch was fine, it pretty much pitched me where I wanted to go and stopped me where I wanted. Is it controllable? yes. Is adequate performance attainable with a tolerable pilot workload? I thought that was an intolerable workload, even though I did come close to getting that. Deficiencies require improvement. Considerable pilot compensation is required for control, you really have to lead it out of the loop slow down your command definitely number 8.

Disk 2 Runs 34 & 35; P4/R16; HQR 3: Really nice, very crisp, I got the roll that I want right away, stopped it right where I wanted to stop it. I could chase things around, pull to them, and it stopped as soon as I got to the pull. The pointing characteristics of the airplane were great. It pointed right where I wanted to and then I could track his attitude real quickly and get right behind him. I would buy that system, it was really well done. The only deficiencies and the only compensation that I could think that I really used is I did kind of relax it a little bit when I got behind it, so I didn't put in a lot of minor movements to excite anything. So once I got on this case, I really fell out of the loop and kind of left it more than I have done on the other ones. Minimal pilot compensation required for desired performance. HQR 3.

Disk 2 Runs 36 & 37; P4/R1; HQR 1: Really nice system, good pointing. The more aggressive I got, the more it responded to me, it didn't go crazy in the box or anything like that, it went exactly where I wanted it. It stopped and started where I wanted. The roll was perfect, it was what I anticipated, and when I wanted to roll out, it rolled out and reversed on me, so it is a really good system. Really good airplane. Is it satisfactory without improvement? Definitely. I would have to say that was a highly desirable system. I didn't have to compensate. I could do anything I wanted to do to that system. It came out to what I wanted, number 1. HQR 1.

Disk 2 Runs 38 & 39; P4/R12; HQR 7: It seemed like it wanted to roll fairly quickly, but I couldn't stop the roll, I couldn't control it, I couldn't pinpoint where I was. So it would roll quickly, but as soon as I wanted it to stop, it would over roll or overshoot and keep rolling on me. I figured out some major compensation was very light to the touch, and I knew that this seems sloppy is the best way to describe it, so if it was light to the touch I could do it and track it and get what I wanted. Is it controllable? yes. Adequate performances was attainable but it wasn't a tolerable pilot workload. Deficiencies require improvement. So controllability was not in question but, however, such major deficiencies that I had to use a lot of compensation. Even though that compensation was letting go and getting out of the loop. HQR 7.

Disk 2 Runs 40 & 41; P4/R7; HQR 4: Overall pretty nice. The roll rate was expected. I would get in, stop it, and then I would pick up rate as I went into it. It was not crisp. I couldn't exactly stop it where I wanted it to stop, it overshot my roll a little bit maybe 10°, 15° each time. A little bit out of the loop in fine tracking. Gross acquisition difficult, fine tracking was very easy. Minor but annoying deficiencies, which is a 4. Desired performance requires moderate pilot compensation. The moderate compensation came in overshooting the roll I had. I had to start rolling out before I really wanted to, so I was not pinpoint crisp. That is the reason for a 4.

Disk 2 Runs 42 & 43; P4/R6; HQR 6: Very slow into response of what I wanted. I put in the input, it would start picking up, and I would have to take out input and I had to leave that input so much it felt like a half an hour of lead time in there. Which translates to about a millionth of a second. I really had to lead it. What I got was real sloppy response. The roll was easy to track something almost purely in pitch, but any roll was in there especially way off to the side was almost impossible to get I couldn't even get the airplane heading at that airplane initially. Is it controllable, yes. Is adequate performance attainable with a tolerable pilot workload? I think I even got desired on that one, but no the workload was not tolerable. Major deficiencies in this one, it was very laggy. Not attainable with maximum. I will give it to you that I got adequate. Very objectionable, but tolerable deficiencies. Adequate performance requires extensive pilot compensation. HQR 6.

Disk 2 Runs 44 & 45; P4/R2; HQR 1: Outstanding one. That one was predictable, I got what I wanted. I put the airplane where I wanted, I had no overshoots. I stopped it and started it from rolling where I wanted it. That is a system you want to

get. Excellent highly desirable system. I went as aggressively as I could, I even backed off if I wanted to. It wasn't a factor how I flew, it was a factor of where I put my airplane. HQR 1.

Disk 2 Runs 46 & 47; P4/R16; HQR 2: Also a very nice system, however, the difference is the more aggressive you got into it, the more bobbling it got. It got to where it was very sensitive as I got very aggressive. I liked the system, but it still had a slight tendency to not overshoot, but get me into a slight overshoot oscillation. It seemed a little bit lack of response when I was extremely aggressive, so when the loop was real tight we had some problems. Pilot compensation was not a factor for desired performance. Maybe the slightest bit, but it had some negligible deficiencies. HQR 2.

Disk 2 Runs 48 & 49; P4/R3; HQR 6: First of all it was really laggy, I could not get the roll I wanted. The only way I could get these suckers shot down is by once I got the airplane tracking towards it, I started rolling out of my tracking before I got behind him. So by the time he was dragging in front of me I was already rolled out and right on a 6. The other thing that was funny I didn't have enough – I wanted more control power. I wanted more action – I wanted to get myself over there. But it didn't fly like a fighter. Slow response, although a controlled response, and slow reaction. A lot of lead time required. Is it controllable? yes. Is adequate performance attainable with a tolerable pilot workload? yes. Is it satisfactory without improvement? no way. Very objectionable but tolerable deficiencies. Adequate performance requires extensive pilot compensation. HQR 6.

Disk 2 Runs 50 & 51; P4/R8; HQR 3: I can grasp it and roll out real quick, the big thing is that I rolled out so quick that sometimes I over rolled out so it bobbled a little bit before I heaved my wings a level to stop my roll. Actually it started me rolling the opposite way. I think it was such a quick rate of getting that roll in and out so snappy and precise. A little too snappy, it gets you a little bit too much. Although I could be really aggressive with it and that is where I found that. Minimal pilot compensation required for desired performance. HQR 3.

Disk 2 Runs 52 & 53; P4/R10; HQR 6: It felt a little laggy. I wasn't getting what I commanded out of it. When I rolled in took a second, and rolled out it took a little time. I had to use a lot of stick throw to get it. An excess amount of stick throw, and an excess amount of time wasted waiting for it to go. The more aggressive I got the worse it became. Bobbling, kind of PIO a little bit in there. But when I just sat back and got completely out of the loop, mellowed out using my whole 15 second, I got them all the time. HQR 6.

Disk 2 Runs 54 & 55; P4/R12; HQR 9: That airplane was not controllable. I would put in a slight command to the left and it had me going before I could get it rolled out. It had me pulling about 360° or plus. I had no control of my roll. As soon as I get slightly aggressive commanding more than 5° to 10° of roll or bank. Pitch was okay though. Is it controllable? no. Not in this mission, the aircraft could fly but it could not do the mission, but basically I could say it is controllable. Is adequate performance attainable with a tolerable pilot workload? no. Major deficiencies. Intense pilot compensation is required to retain control. HQR 9.

Disk 2 Runs 56 & 57; P4/R15; HQR 7: Seemed like it was a little late in rolling out and rolling into what I wanted, so I was getting into this wave action back and forth, and it was not very precise and once again I backed out of the loop. I could shoot it down. Compensation, I basically backed out and didn't command much more than a 1/4 stick throw, and that gave me what I needed. I don't think I reached adequate on that one. There is some major deficiencies. It was not a matter of controllability, it was just a matter of being able to do the task. Adequate performance not attainable with maximum tolerable pilot compensation. HQR 7.

Disk 2 Runs 58 & 59; P4/R1; HQR 3: Not a bad system. It was quick, it would stop me where I wanted to stop, but I didn't seem like I got enough power. I mean I wanted a little quicker roll. I wanted it to be snappier, in and out, so it is still a little slow as far as actual roll rate from the time of commanded until I got 90° of bank, it seemed a little long. I didn't have enough power in my stick is what it felt like. The big thrill is to get little movements. But overall it was pretty well controllable because of the point in characteristics, it stopped and started when I wanted to stop, it was just bit movements in the cockpit. It did require a quite a bit of compensation to overcome that, and learning to make big stick inputs quickly. I did get desired. HQR 3.

Disk 2 Runs 60 & 61; P4/R9; HQR 7: I would have to say that thing was very laggy. I couldn't input a stop roll command quick enough at anything more than an 1/8 or 1/4 of stick. So any large roll command that I asked for slowly developed and no matter how much I led it by, I really could not get it to precisely stop. The major deficiencies are not to control the airplane, it is more in order to do the things, so controllability is not in question. HQR 7.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Date: 23 Feb. 1994; Pilot 1

Runs 30 & 31; P4/R1; HQR 3: I counted one overshoot on each of the two sequences. I would put that in the desirable I believe. I would put the Cooper Harper Rating as a 3. Some mildly unpleasant deficiencies. The compensation was still minimal. Wasn't in the moderate at all. Slightly worse than the base line but not much. HQR 3

Runs 32 & 33; P4/R7; HQR 8: Is it controllable? barely. Is adequate performance attainable with a tolerable pilot workload? no. Many times when I would easily get into a roll PIO, and I counted at least 4 times well developed, I had to back way off my gain to get out of it. Even then I would still have a minor roll PIO as I'm zeroing in. It was considerable. HQR 8.

Runs 34 & 35; P4/R6; HQR 8: Is it controllable? barely. Is adequate performance attainable with a tolerable pilot workload? no. Multiple overshoots, multiple PIOs. This was slightly worse than last configuration. It was more sluggish, so I held the stick longer and when I took the stick out, it overshot even more. Considerable pilot compensations required for control. I would give it the same rating as the other one. Although side by side this one was worse than the last one. HQR 8.

Runs 36 & 37; P4/R8; HQR 7: Is it controllable? yes. Although there are occasions where it is very surprising at the response. Is adequate performance attainable with a tolerable pilot workload? no. I believe I overshot three times on each of those sequences. It is just barely in the 7 category. Adequate performance is marginal somewhere between 6 or 7. I would say by the strict definitions, since I did not meet the adequate criteria, it is a 7. HQR 7.

Runs 38 & 39; P4/R16; HQR 7: Although there were periods again of large amplitude PIOs as before. I overshot on at least four out of 6 of each of the two series. Adequate performance was not attainable. However the controllability was not a question. There appeared to be plenty of rate available, but controlling that rate was a real trick. HQR 7.

Runs 40 & 41; P4/R2; HQR 4: I did achieve desired performance although I was working very hard to do so. That would by the chart give it a 4. Although subjectively I think it feels more like a 5. The reason being it was predictable most of the time. And then about one time out of 1 or 2 times of each run of 6 it would do something totally unexpected. But by the chart and the criteria it was a 4. Although I did not like it. HQR 4.

Runs 42 & 43; P4/R17; HQR 3: Desired performance was achieved. Overall very good. Occasionally, though, especially with the larger amplitude stick inputs, it was a little unpredictable right along the edges, which required compensation. Therefore I will give it a 3. Not quite to 4 level but below, 3. HQR 3.

Runs 44 & 45; P4/R7; HQR 5: Is it controllable? yes. Although on one occasion I got into a very mild PIO and easily got out of it. Is adequate performance attainable with a tolerable pilot workload? yes. Desired performance was not. Adequate performance requires considerable pilot compensation. HQR 5.

Runs 46 & 47; P4/R10; HQR 7:

Is it controllable? yes. Although there were occasions where I got into mildly damped PIO. Adequate performance was not attainable due to the large number of overshoots. Controllability was really not a question. HQR 7.

Runs 48 & 49; P4/R1; HQR 4: Desired performance was achieved. Although it took some amount of work to get there. Good roll response, good roll rate. Sometimes it was hard to predict. Desired performance requires moderate pilot compensation. HQR 4.

Runs 50 & 51; P4/R8; HQR 4: Desired performance was achieved with a fair amount of work. It appeared the initial roll in was more sluggish than I would have liked. Desired performance requires moderate pilot compensation. HQR 4.

Runs 52 & 53; P4/R16; HQR 6: Is it controllable? most of the time. One minor PIO. Is adequate performance attainable with a tolerable pilot workload? yes. Desired performance is not attainable. I had two overshoots on each of the two sets of runs. Adequate performance requires extensive pilot compensation. HQR 6.

Runs 54 & 55; P4/R2; HQR 3: Just a bit more than the base line I felt like, so rather than a 2, I will go with a 3. HQR 3.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 56 & 57; P4/R3; HQR 7: No question on controllability. It is so sluggish it is hard to make it do anything. Is adequate performance attainable with a tolerable pilot workload? no, I think on the first run I overshot numerous times, and the 2nd time only twice, although it was a matter of extensive compensation. Between a 6 or 7, but I would go with a seven. HQR 7.

Runs 58 & 59; P4/R11; HQR 5: Is it controllable? yes, although very oscillatory, I found myself in a constant minor roll PIO there, nearly on every run. Nevertheless I was able to achieve adequate performance with fairly extensive compensation. HQR 5.

Runs 60 & 61; P4/R9; HQR 9: Is it controllable? barely, as soon as I closed the loop, it starts to diverge in roll PIO. HQR 9.

Runs 62 & 63; P4/R7; HQR 5: Is it controllable? yes. I could achieve adequate but not desired performance Adequate performance requires considerable pilot compensation. I objected strongly to the tendency to oscillate and roll. I could never quite settle it out. Always seemed to be lag in my input. HQR 5.

Runs 64 & 65; P4/R8; HQR 3: Very good configuration, it is controllable. Adequate performance easily achieved. Desired performance also easily achieved. HQR 3, because I felt like I worked just a tad harder than I did on the baseline. It felt just a little bit more sluggish on the roll in, not quite as crisp.

Runs 66 & 67; P4/R10; HQR 5: Is it controllable? yes. Is adequate performance attainable with a tolerable pilot workload? yes, but only with a lot of compensation. Very oscillatory, very difficult to predict. HQR 5.

Runs 68, 69 & 70; P4/R1; HQR 1: Very good configuration. Desirable performance was easy to achieve. The only thing I was trying to figure out is whether it was between a 2 or 3. I am going to give it a 3 although I can't tell for sure why. It seemed, if anything, a little bit too fast on the roll. Although it is very hard to put my finger on what it was. It was a little worse than the baseline. HQR 3.

Run 71; P4/R15; HQR 10: I had to quit doing the task in order to gain control of the airplane. Just constant PIO whenever I tried to do the task, either neutrally damped or divergent. So I had to just quit doing the task and do it open-loop in order to try and capture the target.

Runs 72 & 73; P4/R16; HQR 5: Is it controllable? yes. Is adequate performance attainable with a tolerable pilot workload? yes. Desirable no. I always felt as though I was right on the edge of going into a PIO. But I could still achieve adequate performance. HQR 5.

Runs 74 & 75; P4/R5; HQR 3: Is it controllable? yes. Although based on that first open-loop, the original gain I had some questions about that, however, after we lowered the forward loop gain down, it was actually very good. A couple of times I overshot and it was a little bit too fast in the response. HQR 3.

Runs 76 & 77; P4/R6; HQR 7: Is it controllable? yes. I didn't get the PIOs I got on some of the others. Very sluggish response. This one was very sluggish I could not achieve adequate performance. Controllability was not an issue.

Runs 78; P4/R2; HQR 2: It is either a 1 or 2. It's a 2. Good as the baseline. Nothing I could put my finger on.

<u>Date: 24 Feb. 1994: Pilot 3</u>

Runs 1 & 2; P4/R1; HQR 4: Overall I felt like I didn't get a very quick roll rate, it wasn't responding to what I wanted. I wanted it to snap in and snap out of the roll and it seemed like it was kind of pushing in and pushing out. I never really got it. I had to really lead the roll out and roll in. Found that more of a problem in gross acquisition. Once it was in fine track, I noticed my stick movements were really exaggerated, so a lot of pilot compensation, lot of quick throws, big throws in order to get it done. Although I hit desired on all of these I would say there were some minor but annoying deficiencies. Desired performance requires moderate pilot compensation. HQR 4.

Runs 3 & 4; P4/R7; HQR 6: Overall I felt like I wasn't getting the roll that I wanted quick enough. I was commanding and waiting. It almost seemed like I was going to stop. It wasn't giving me something. It didn't give me the speed of onset that

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

I wanted. It did roll me pretty good once I started rolling, but it just didn't get me out there, felt like I need another 8" on the stick and in roll axis.
Very objectionable somewhere between the considerable compensation and the extensive compensation. Will give it a 6 because the amount of stick throw I was having to use. My arm was actually getting sore from having to do that one. HQR 6.

Runs 5 & 6; P4/R14; HQR 7: I kept overshooting how much roll I want on this. I had roll in, but I couldn't stop how much I wanted until it was much too late and it was pretty quick roll so I really couldn't lead it as much as I would like to. So if I would start rolling, I wanted to roll out, now I had to lead it by a lot, but I really didn't have enough time to lead it because it rolled so fast. It delayed rolling me in and out but as soon as it started to roll it rolled too quick. I went all over the place on this, but as soon as I tried any fine tracking at all, once I got it into that circle and tried to keep it there, it just exasperated the whole problem. I did not achieve that adequate. Major deficiencies. Controllability not a question. HQR 7.

Runs 7 & 8; P4/R17; HQR 3: Very sensitive to my roll. It was really nice in and out, but it started rolling a little too quick. As soon as I touched the stick, it rolled a little bit, so I found myself doing little bitsy wobbles. Tendency to have a little problem trying to track it. Gross acquisition was a lot easier, but fine tracking was still a little problem, but not really noticeable. I would buy that system and put it on the airplane, but there are some unpleasant deficiencies. Minimal pilot compensation required for desired performance. Once you got it in there you kind of get hands off a little bit, relax, because you don't want to bobble around your airplane. HQR 3.

Runs 9 & 10; P4/R16; HQR 4: I didn't achieve desirable on there although I though it was a pretty good system. The only thing I could really detect on this as I was trying to finish my roll to get behind the airplane and match bank angle with him, I had a hard time centering or stopping it at zero bank. I kept overshooting, waffling around a little bit behind him. I didn't quite achieve desired although I got adequate. I would like to give it a 4, although I really like to give it a 3, but I can't give it a 3 because I didn't get desired.

Runs 11 & 12; P4/R1; HQR 2: Very nice system. The only comment that I seem to have a problem is that for my big rolls when it was way offset right or left and I wanted to get over there, I really had to command a lot of stick in order to get the roll going, but otherwise it is stopping and starting. Small rolls, small movements seem very nice. It was crisp and it was precise, it was what you would like to see. Good system – Negligible deficiencies. Pilot compensation not a factor for desired performance. I did the whole thing with minimal compensation. HQR 2.

Runs 13 & 14; P4/R3; HQR 7: Overall the roll rate was way too slow and the amount of stick available, I didn't have enough. I wanted to be able to bend the thing off the stops in order to pick up the roll rate, but no matter how far I pushed it, the roll rate never picked up. Although it did start rolling out and start rolling in when I initiated it, there was not a lot of delay in that, it just rolled so slow. Is it controllable? yes. I could not attain adequate performance with a tolerable pilot workload. Major deficiencies. Considerable pilot compensation is needed but controllability is not a question for the aircraft. HQR 7.

Runs 15 & 16; P4/R11; HQR 3: Overall a pretty nice system, but I found the more aggressive I got, the more chance I had to PIO. Otherwise when you sat back and just flew it, relaxed, it flew extremely well. It pointed to what you wanted, it was very crisp. As soon as I felt like my adrenaline was up and I wanted a full roll rate on it, I couldn't stop the roll rate quick enough so it was almost too much roll for full stick throws. Mildly unpleasant deficiencies. If I wanted 90° of bank to chase after something and wanted to command it now, I didn't get it now, and when I finally got it, there was a little overshoot. Minimal pilot compensation required for desired performance. HQR 3.

Runs 17 & 18; P4/R6; HQR 6: Overall the system was very slow in response in roll. I wanted to roll out of it and I just didn't get it. I really came off the stick and was Mr. smooth, I couldn't be as aggressive with this system. I couldn't roll pull it over there and roll out on a point because by the time I rolled over there and I tried to roll out the airplane I overshot. HQR 6.

Rums 19 & 20; P4/R5; HQR 1: Overall a very nice system. I could almost say it was mistake free. No matter where I put the airplane, it wanted to go there although I could of used a little more sensitivity, and a little more power. It seemed a tad bit quicker in roll but not too much, otherwise it was very nice. Highly desirable. Pilot compensation not a factor. HQR 1.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Debrief Target Acquisition Task:

The task I liked a lot, putting airplanes in different parts of the quadrant and chasing after them. If I wanted to relax my gains or lower my gains I could easily and still accomplish the task in 15 sec. I would recommend shortening the task to maybe 10 sec. It is a lot more mission, operational realistic to shorten the task here. The second thing is, if it is possible once I lock him up it might be neat to start throwing in maneuvers of the target. I don't know if that is possible moving your target around a lot more. It seems like and that will show your perturbations of roll more. [comment – when we original set up the task the target were out more to the two sides of the cockpit. We are looking at moderate maneuvers, and when all the targets were very shallow and far out to the sides, the pilots when they were flying and testing out the maneuver were peaked over all the time, and we were not getting any of the moderate maneuvering, so that is why we brought them in.] – That is fine bringing the targets in, what I am saying though, once I acquired the target if the target moved a little more, what that will do is exasperate my control authority, but the key is once you get that, you have to control that, that is just another variable.

Ground Attack Task:

Runs 21 thru 24; P4/R1; HQR 5: I would have to say overall the roll seemed to be very reliable. It got me to where I wanted quickly, it was very responsive and roll is very good, in fact it was almost to a point of overly sensitive when I got to the ground. Is it controllable? yes. Is adequate performance attainable with a tolerable pilot workload? yes. Is it satisfactory without improvement? no, because all I could achieve was adequate on three of the runs and desired on one. Moderately objectionable deficiencies. Adequate performance requires considerable pilot compensation. I had to work hard to get it tracked and rolled right on the runway. The fine rolling and tracking the heading was the big key there. HQR 5.

Runs 25 thru 28; P4/R7; HQR 3: Over all it seemed like the roll was a little sensitive trying to get my small corrections in at the end. I overcontrolled it a little bit, had a tendency for slight overcontrol. Had to fine tune the runway heading, but I did get a response that I wanted. HQR 3.

Runs 29 thru 32; P4/R10; HQR 6: Seemed like I could not roll the airplane fast enough into and out of the bank, so what happened by rolling into any long time roll in, I had a hard time controlling my altitude. The airplane kind of slipped out of the sky. It took forever to roll in and roll out. HQR 6.

Runs 33 thru 36; P4/R2; HQR 7: I would have to say the roll rate was pretty good. Once I got rolling it was pretty good, it just seemed like it was a little slow to start my roll. Really didn't seem to have enough power in the task. I wanted to use more roll rate to stop it in a level flight, before I get decoupled. HQR 7.

Runs 37 thru 40; P4/R16; HQR 3: I seemed to get better pitch control predictability. I didn't overcontrol as much. What that means is when I wanted to roll out, I got a roll out, and when I didn't want to rollout I didn't. Small stick movements, but as soon as I commanded 90° of bank, I want to snap it, and I still was not getting that, so it was still slow. HQR 3.

Runs 41 thru 44; P4/R1; HQR 5: Rolls in is pretty good, it just doesn't roll out. I need a little faster roll in order to stop me from tracking heading every time I want to roll. The airplane was not responsive enough for me to correct at low altitude is how I felt. I would say it had some moderately objectionable deficiencies. It was in there, but I had to get my corrections up high then dive bomb. HQR 5.

Runs 45 thru 48; PR/R6; HQR 7: I felt like the roll rate was way too slow. It was more apparent in the faraway offsets than the close. So what I did, I took one correction and took what I got so I could not refine it at all because I know as soon as I ask for something more it would be unresponsive. Basically I could not finally ask for any kind of heading or bank change because it was unpredictable. It was slow and didn't seem like I had enough control power. Major deficiencies, it is not a question of controllability, it is just a problem doing the task. HQR 7.

Runs 49 thru 52; P4/R7; HQR 4: Fairly good system. Seemed to get just a little bit of problem predicting exactly my rate of roll out. Once I started, it developed fairly quick, and then I had to take it out pretty quick, and I had a chance to bobble at the end of the roll outs. When you got really aggressive with it, it almost became saturated I would say I couldn't lead enough. HQR 4.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 53 thru 56; P4/R17; HQR 3: On this one I felt like I had really good control authority. I could point the airplane where I wanted it and predict my roll in and roll out. It almost felt normal for how an airplane should fly a dive bombing type of pattern. I could aggressively get over there to my outline on, and then once I got on my line on, I could move around the elevator pitch authority in order to set my path, and I was pretty much right on the line. HQR 3. Slight unpleasant things in that one, mostly being like just a little bit more authority, little less push for the amount of action I got.

Runs 57 thru 60; P4/R15; HQR 7: It seems like I got a real slow response to what I wanted the rate in and rate out, so it caused me to over control, overshoot, undershoot, and I guess there is not time to learn how good your system is as you are driving down the track here, so you don't know if you need lead or not. I started leading it a lot and it still didn't give me what I wanted. HQR 7.

Runs 61 thru 64; P4/R2; HQR 6: It seems like my roll was difficult as far as I didn't seem to get it as quick as I wanted. Once I got it, it did come in and out okay, but it wasn't a very fast roll rate so it wasn't responsive enough, and you can tell pretty much by my offset on the runway heading. HQR 6.

Debrief of Ground Attack Task:

The task overall, I like the idea of two far offsets and two close offsets. The close offsets give me an idea how my fine tracking or my fine roll authority is. Long ones ask me how good gross tracking is, it is a very difficult task to do. You cannot let your gains down at all. You can on the inside ones a little bit, you kind of achieve adequate almost every time, but you cannot on the ones that are far away. I would have to say that the only thing is that in order to help the pilot do the task and know what his parameters were, is if he can throw a freeze on the trigger or something like that so as soon as he presses it, it freezes the parameters and he can see exactly where he is. Also, it is difficult without focusing on the altimeter to decide what your altitude is, gain or loss. So if you want to put a building or something closer to the runway, it might be easier to check on, because you will have a relative height idea that close to the ground. But a really good task I think for exciting the pilots gains and checking the systems. It is very hard for the pilot to comment because things happen so quick and there is not a lot to realize except that he misses the target and he couldn't get as much roll as he wanted or it wasn't as quick.

Date: 24 Feb. 1994; Pilot 1

Runs 1 & 2; P4/R1; HQR 2: Is it controllable? yes. Is adequate and desirable performance easily achieved with virtually no compensation and I liked that configuration a lot. HQR 2.

Run 3; P4/R12; HQR 10: Any time I closed the loop and tried to control the airplane for the target, it got into a divergent roll PIO. The only way to fly it was essentially open-loop toward the target without bringing the target into the crosscheck. HQR 10.

Runs 4 & 5; P4/R13; HQR 6: Is it controllable? yes, although it was extremely oscillatory. I felt like I achieved adequate performance only just barely and it took a great deal of compensation to dampen out the oscillations. HQR 6

Runs 6 & 7; P4/R17; HQR 3: Very good configuration, I could achieve adequate and desirable performance. It didn't feel quite as good as the best ones we have looked at. It didn't seem to roll in quite as crisply and I wasn't able to stop it quite where I wanted it. HQR 3.

Runs 8 & 9; P4/R16; HQR 5: It was controllable although it was very oscillatory. I could achieve adequate and almost desirable. Tendency to overshoot and oscillate both. HQR 5.

Runs 10 & 11; P4/R14; HQR 5: I can just about say the things I said the last time. I could achieve adequate performance, but not desirable because it was very oscillatory. Hard to predict where I was going to stop after I made an input. I achieved adequate performance but it required considerable pilot compensation. HQR 5.

Runs 12 & 13; P4/R10; HQR 5: Not quite as bad as the other two, but very similar in that it is oscillatory, not as bad. Still could not achieve desirable performance although it was much closer than on the last two configurations. HQR 5.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 14 thru 16; P4/R5; HQR 4: Is it controllable? yes. Is adequate performance attainable with a tolerable pilot workload? yes. The question is from a decision tree, is it satisfactory without improvement? There is something I don't like about it and in spite of three runs, I can't put my finger on what it is. I could achieve the desired performance, nonetheless, with some moderate compensation. HQR 4. Can't tell you why.

Runs 17 & 18; P4/R7; HQR 5: Is it controllable? no oscillatory tendency. However, I was very bothered by the sluggish initial roll. Max roll rate was okay, but the build up was too slow, the rolling time constant was too long. HQR 5.

Runs 19 & 20; P4/R3; HQR 7: It was controllable, but could not achieve the adequate performance, because of multiple overshoots. Very sluggish maximum roll rate, even with the higher gains. HQR 7.

Runs 21 thru 23; P4/R8; HQR 3: As one of the other runs awhile back, the decision, is it satisfactory without improvement? I could achieve desired performance, but again there was something I couldn't quite put my finger on that made it hard to predict. HQR 3.

Runs 24 & 25; P4/R16; HQR 5: I could not achieve desirable, but I could achieve adequate, just a very slight indication of oscillatory tendency. Required considerable pilot compensation HQR 5.

Runs 26 & 27; P4/R13; HQR 7: Numerous overshoots, difficult to control. Never felt controllability was a question, although it was very oscillatory, and had to almost go open loop to get out of one of them. HQR 7.

Runs 28 & 29; P4/R14; HQR 4: Easily controllable. Adequate performance achieved, desired performance took a little more work. HQR 4. Sluggish initial roll in made it little difficult to capture the points I wanted it to.

Debrief on Target Acquisition Task:

Over all a really super task. I liked this as much as any I have ever seen. I will only make two comments on it, not enough of the targets are far out at the extremes. Usually only one or two per run. I would like to see one more, because some of those configurations really didn't show up how badly they were until you tried to make a 90° turn to pull over there, and that is when they really showed how bad they were. Not a whole lot more, I would just like to see one more that requires a large input *vs.* a smaller one. Overall the spread of the targets are pretty good. The second comment that I have is there is no incentive to do the task fast. I still feel the time is too long, particularly it doesn't differentiate between the good configuration where you can nail in 3 or 4 sec. *vs.* a configuration that is much worse and takes all 15 sec, yet theoretically they would get the same Cooper-Harper rating if I did not overshoot. If I used all 15 seconds but I didn't overshoot and I achieved the task I would get the same rating as a configuration where I could just nail it in under 5 seconds, and I think that is wrong. I have yesterday and today flown the same way and that is, I tried to consistently do it in the minimum amount of time even though there was no incentive to do so. I guess my only comment on how to improve that would be for desired performance to decrease the time to 10 sec or something like that and maybe knock off a second or two off the adequate. I still feel like it is too long for a configuration that you would really like. It doesn't need to be an even number, because you are just looking at the count down bar, it is more function of how wide spread your targets are. Again I feel like taking a second off the adequate and 5 sec off the desirable would force the pilot into a more aggressive attitude, but these comments are overall minor. I thought the task was really super and forces you to all the axes and I felt it was superior in differentiation using the Cooper-Harper scale. I thought that I was fairly well able to go down the decision tree and pick out the right answer. Typically the only ones I had real problems with were ones that fell between and 3 or 4 whether it warranted improvement or not. Overall it did a real good job of helping me differentiate. The overshoots 1 *vs.* 2 for adequate desired, I think is right on. I would not change that. It is perhaps the best differentiator you have between desired and adequate.

Runs 30 thru 33; P4/R1; HQR 2: No problems with control. I achieved desired performance on all 4 runs. I really felt as good or better compared to the baseline that I was practicing with. I felt like I didn't have to compensate as much at all on that one. HQR 2.

Runs 34 thru 38; P4/R7; HQR 3: Is it controllable? yes. I achieved desired performance. It was not as good as the previous configuration. I thought the roll response was a little sluggish. HQR 3.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 39 thru 43; P4/R10; HQR 4: Is it controllable? yes. I achieved desired performance, it took more work than it did on the previous 2. Wasn't getting the crisp roll response. HQR 4.

Runs 44 thru 47; P4/R6; HQR 7: I achieved adequate performance on 2. I didn't achieve adequate performance on the other runs. Controllability was not in question. At one time I flew into the ground because I over banked it and could not get out of it. HQR 7.

Runs 48 thru 52; P4/R16; HQR 5: No controllability problems. Adequate performance was attainable. Desired performance was not attainable. HQR 5.

Runs 53 thru 56; P4/R2; HQR 2: I had no problems, minimal compensation. HQR 2.

Runs 57 thru 60; P4/R3; HQR 7: Extremely sluggish. So much so I could not achieve adequate performance on any of the 4 runs. Controllability was not in question. HQR 7.

Runs 62 thru 65; P4/R15; HQR 6: It is controllable, although on the very first run I almost did lose control on it. If I kept the inputs small and gentle as possible, it flew very well. It felt like rate limiting. Extensive pilot compensation. I had to keep the inputs very small and very smooth. HQR 6.

Runs 66 thru 72; P4/R1; HQR 4: No problem with control. I could achieve adequate performance and just barely desired, and I don't know why. It seemed to fly very well, seemed very responsive, but I on many of those runs I would be just outside the desired on the ones I didn't make it. HQR 4.

Runs 73 thru 79; P4/R10; HQR 5: Is controllable. I could achieve adequate. I could almost achieve desired, but not quite. Whenever I pushed it, if I had to make an aggressive input, it lagged so bad and that made it moderately objectionable. HQR 5.

Runs 80 thru 83; P4/R9; HQR 8: Is controllable most of the time. does take considerable pilot compensation to keep it control, have to always be aware of making small controlled inputs. HQR 8.

Debrief of Ground Attack Task:

I have one big comment and that is that the detail is all out front. You have to make small controlled inputs even with the good configurations. If you think back when I first started the task, I was very aggressive and I couldn't do the task. As soon as I backed off and tried to be smooth about it, I could do the task fairly easily with the good configurations. Even with some of the bad ones it seems like I could. What that kind of masks is by doing small controlled smooth inputs it masks the rate limiting problems, I believe. Occasionally I could feel it right at the edge, right on the edge of my input there was something going on, but as long as I kept my inputs small, and small inputs were all that were required to get the desirable outcome on the task, then I was okay, but I could feel it right there on the edge. I just wasn't quite pushing hard enough to get there. That is unfortunately just the nature of being in the sim. There is not enough detail in the ground along the edges to make anything but smooth inputs to accomplish the task. I have no doubt about that I can tell the differences. I feel like some of the rate limiting cases maybe worse. I am guessing they may be worse than what I rate them, because I feel that something is going on, but as long as I keep my inputs small I still accomplish the task. On one of those, I forget which one, the first time I put in a large input on the outside position and I almost rolled and inverted. This is terrible, the next time, I just made a smooth controlled roll input and a smooth roll out, and I nailed it, and I was able to nail it every time by doing it in that manner.

Date: 25 Feb. 1994: Pilot 3

Debrief of Ground Attack Task:

I aggressively pulled over to the left to get what I want. Now I am pulling back to the right, I got the runway in sight and I liked to pull down on it a little bit. Now when I roll out I get a little effect of where I am not really pulling right onto the point I want, coming up to release, a little high and pull off. I guess the best thing out of that is I got the roll rate I wanted, but

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

I didn't get the high refining roll rates etc. I could come up with a few comments about how good it was, but it would be limited, and you can see that I didn't even get probably adequate on that. It was pretty difficult.

This is a close-in one from the right, pull in over hard, pull back to the left, now see my roll out and boom. Altitude control is a problem, it is quite off to the left, but it seemed like I am throwing my stick quite a bit just to get me left and right, but that is really how I want to fly that one and pinpoint as early as possible so I have the longest straight in run possible on my target run. That's doing it aggressive, now let's do it really mellow on the airplane. It is kind of unnatural to a fighter pilot because you are not going to sit and mellow out with your controls as you approach your target. Here comes a mellow one from the right, nice smooth roll, glides up there and back, get it out, come up, release and, adequate. I really couldn't tell much about my roll, because you can see I hardly used my roll on that one. I can't give you a whole lot of good comments about the airplane, I just said well, it rolls a little bit, it seemed like the roll rate I wanted.

We do one from the far left I think it is now. I will use a mellower technique from that or a lower gain would be a better way to describe it. I am going to pull my airplane over nice smooth roll and the reason I am doing a smooth roll is because I have kind of learned that in this airplane the harder I roll the more I get some kind of yaw out of it and I don't get pinpointing accuracy. Once again I couldn't tell you a whole lot about it. Ideally, I want to be perfectly lined up on this thing and make a lot of small corrections with a higher rate as I get closer to my target in order to get the perfect lineup.

Same thing except let's switch our point down to the middle of the runway or something where we are trying to bomb. Lets just see if I can achieve it and still get some good gains out of the task. I am going to pull left once again just let it fly over here like I always do and pull right. Now, I am off to the left, I can pull left again. Pull right. Here comes my point. You can get a little better setup. You can find out a lot about the airplane, not so much about the rolls. I don't know if that helped a little or not. Lets try it with this shorter end one. Might need to put a big X in the runway somewhere, or something like that, it is just a trial by error now. The task is very difficult. Pull, pull back, okay get that sucker down there. Okay good now, alright that is how I want to be. Here comes my dive bomb, release out. I released a little high on that, but you see I was perfectly lined up I could make a few corrections, I could check on my roll rate a little bit while I was doing it. It was a doable maneuver. I guess what I would say is in designing the maneuver 1) adequate was something that was mission applicable, well was that really mission applicable? I would say that was almost too difficult. When I come up with desired I want something that is doable, but also shows me the problems with my system. So you almost want me to correct the zero error in order to get the high rate resolution out of there. I guess it is more of a checking for PIO but you want to get that pilot some gain up there. We will do a high gain type task again trying to go for a zero error response centerline midway down the runway bomb on this one. We will do it off to the side, here it comes, a big pull over here, get me set up early, see I want to set up early now I want to bring it back. Okay, I jerk this sucker around. You don't just play with an airplane nice and smooth like a airliner. Now I am back on, now I am expecting a better one. Now coming down — bomb — boom and off. You can see a couple things here. I like the maneuver a little high and real close to the ground.

Runs 9 & 10; P4/R1; HQR 3: Overall the roll seemed pretty good. Seemed a little slower than what I wanted not real crisp. I seemed to bobble around pitch, when I pull the pitch up to long distance acquire, I get the gross acquisition done and bobble around I usually overshot it once or twice every time I went for a gross acquisition. Once I butted into fine, I found out I was making quite a few little bitsy stick movements probably for no reason but I felt like I was working a slightly sensitive system. It just bobbles around in pitch. I don't mind pitch problems too much because you can fix that and it doesn't take a whole lot of work, your arm doesn't get tired. I would give it a 3. Minimal pilot compensation required relaxing on my fine tracking was the compensation. HQR 3.

Runs 11 & 12; P4+20/R1; HQR 4: I really disliked (this config.). I could easily separate the pitch and roll on this task. They weren't harmonious in the way that they worked. The roll was nice and sharp, I could capture when I isolated the aircraft to just getting directly behind it. In level flight I could roll around it perfectly, so I really liked the roll. In pitch, I overshoot drastically, I would say it seemed like it was really lagging what control I was putting in and it was very difficult to track. Fine track up and down. HQR 4.

Runs 13 & 14; P4+40/R1; HQR 1: I liked that system a lot. It was very sensitive it stopped me as soon I stopped the control input since I wanted opposite control input. It went dead stop, no lead time required at all. Roll was very nice, sharp, crisp and easy to follow. HQR 1.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 15 & 16; P4+80/R8; HQR 4: It took me a little bit to get the airplane going. A little more effort on the stick than was required before and it took me just a second for the airplane to respond to what I needed. Mostly in pitch, and roll I felt that it was a little heavier in roll. I rolled a little slower than what I would like, I wanted it a little more crisp so I had to lead it in roll. Pitch I felt like I had to command a lot more than I initially wanted in order to get the response I wanted. Then I had to command more to get it out. HQR 4.

Runs 17 & 18; P4+40/R7; HQR 5: The pitch was very sensitive, it got me where I wanted to go quick but almost too quick to where I overshot. The roll seemed a little slow seemed like I was a little heavy. I needed a little quicker and snappier roll rate, little more crisp. Moderately objectionable deficiencies. Deficiencies being that the pitch was too fast and the roll was too heavy, I didn't have enough quickness, response didn't roll fast enough for the amount of stick I had to put into it. For pitch I put just hardly any stick, once I got going I had to really lead it to stop it. HQR 5.

Runs 19 & 20; P4+20/R6; HQR 7: Overall I wanted to get the airplane moving and so I used a lot of stick and finally it would start moving. I would have to put in opposite stick in order to stop it because it would move too far. Once it started moving it seemed to move at a good pace, but it took forever to get to move and I used a lot of controls to do it in both pitch and roll. Almost intolerable workload. HQR 7.

Runs 21 & 22; P4+80/R1; HQR 3: I bobbled around the exact tracking I wanted. It took me a little bit to get it there. It got there quick, but I had bobble around it so I couldn't exactly put it where I wanted it at all time. HQR 3.

Runs 23 & 24; P3/R1; HQR 4: It seemed fairly good in roll. A little slow in the roll, not as crisp as I would for it to be. The pitch was too crisp it got to be overly sensitive where I was trying to stop it on a point and I found out I would be stopping it too early then have to put more in. Extremely overly responsive in pitch. HQR 4.

Runs 25 & 26; P4+20/R1; HQR 6: Very nice airplane. Roll was very responsive. Worked real well. Pitch I would have to say it seems to delay my input and once it put it in, and put it in really quick, then I couldn't lead it fast enough to get it out. So I was using huge control inputs and finding out that I automatically went to massive control inputs each time. Unharmonious with the roll. HQR 6, even though I hit desired performance on this one.

Runs 27 & 28; P4/R1; HQR 3: Pretty good system. The roll was good. It seemed like the pitch had a whipping tendency is the best way to describe. It takes just a little bit to get it going and all of a sudden it whipped me up there so I would have to try to stop it. Either I stopped too early or stopped too late. Just a tad bit of PIO susceptibility. Slight bit of lag in it and it zipped across the sky. HQR 3.

Runs 29 & 30; P4+40/R1; HQR 2: Really nice system, the roll seemed pretty good. The pitch seemed pretty good just a tab bit quick in pitch rate. HQR 2.

Runs 31 & 32; P4+40/R7; HQR 4: The pitch rate was good the roll rate, wasn't as good. HQR 4.

<u>Date: 25 Feb. 1994; Pilot 1</u>

Runs 33 & 34; P4/R1; HQR 2: Achieved desirable performance rather easily. Overall Cooper-Harper 2. Ever so slightly worse than the baseline, and I only saw that on a couple of cases where I overshot just a little bit. But overall still a 2.

Runs 35 & 36; P4+40/R1; HQR 5: I think it is satisfactory in that I achieved adequate performance, but it took a fair amount of compensation. It has a real tendency to overshoot and then have to come back, it is not at all oscillatory though, overall HQR 5.

Runs 37 & 38; P4/R15; HQR 8: I could not achieve adequate performance, primarily because the targets that were offset from center required large or moderate control input. I would get into severe PIOs. The first time I went literally out of control and on several occasions I had to completely back off. You just do an open loop maneuver just to stay in control. Overall an 8. HQR 8. It is controllable, adequate performance was not attainable due to the number of overshoots. A couple of times I got into PIOs although they damp themselves out. It was very hard to stabilize the pipper on the target. Overall a 7. HQR 7.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 41, 42 & 43; P4+80/R8; HQR 3: It falls somewhere between a 3 and a 4, it all depends on whether I think it warrants improvement. It is a little bit worse than the baseline and the pitch seems ever so slightly oscillatory, very minor if at all noticeable. Actually my biggest complaint was the roll response which was slightly sluggish. Overall a 3. HQR 3.

Runs 44 & 45; P4+40/R7; HQR 6: It is controllable. Could not achieve desired performance, I could achieve adequate performance, but the roll dynamics were very objectionable. Overall a 6. HQR. 6

Runs 46 & 47; P3/R1; HQR 4: That one is very interesting, roll dynamics were good. The pitch dynamics had a dropback almost like a classic second order system *vs.* a pitch rate system. It was somewhat annoying. Nonetheless I could achieve desired performance. Once I figured out what was going on I could predict it fairly well. Overall a 4. HQR 4.

Runs 48 & 49; P4+20/R6; HQR 7: Is it controllable? yes. Is adequate performance attainable with a tolerable pilot workload? no. Very sluggish in both pitch and roll axis, which led to overshoots in both axes. Overall a 7. Controllability was not in question. But I could not achieve adequate performance. HQR 7.

Runs 50 & 51; P4+80/R1; HQR 2: Nothing objectionable around either axes. HQR 2.

Runs 52, 53 & 54; P4+40/R1; HQR 4: Overall pretty good on the close in targets. I seemed to have a problem I kept overshooting a little bit. I can't put my finger on why it was, but it was annoying. HQR 4.

Runs 55 & 56; P4/R11; HQR 4: The roll response was sluggish with large inputs that made it a little hard to predict, consequently I overshot occasionally. Pitch maybe just a tad more oscillatory from the baseline. HQR 4.

Runs 57 & 58; P4+20/R1; HQR 7: The pitch appeared to have a rate limit or something. It was very difficult to control, very difficult to predict on the large inputs, on the small inputs not too bad. I could not achieve adequate performance because of the numerous overshoots, but other than very minor PIOs it damped itself out on the large inputs. Controllability was not in question. HQR 7.

Runs 59 & 60; P3/R1; HQR 4: Same drawn back in pitch that I saw on earlier runs. After I make my inputs and stabilize it, the nose drops a couple degrees. Very annoying. Overall a 4. HQR 4.

Runs 61 & 62; P4+20/R6; HQR 7: It was a sluggish response in roll primarily and I didn't notice it until I did more pure pitch maneuvers. Also sluggish response in pitch. However the roll more or less over shadowed it. Either case I could not achieve adequate performance because of the number of overshoots. HQR 7.

Runs 63 & 64; P4+80/R1; HQR 2: Okay, I had no problems. HQR 2

Runs 65 thru 68; PR/R8; HQR 3: I really didn't notice anything wrong with that one at all. Although it did require some compensation. I can't put my finger on why it is. Overall a 3. HQR 3

Runs 69 thru 72; P4/R14; HQR 8: I could not achieve adequate performance routinely on those close inside. In fact control was some time in question. Overall an 8. HQR 8.

Runs 73 thru 76; P4/R12; HQR 10: I lost control on all 4 attempts. HQR 10.

Runs 77 thru 80; P4/R5; HQR 3: It was just a little bit more sensitive in roll than I would have liked, perhaps we could of backed off on the gain a little bit more. Overall a 3. HQR 3.

Runs 81 thru 84; P4/R10; HQR 4: Overall, when I made small inputs it responded well, I noticed on the larger inputs it tended to lag. I really didn't get into a situation where that showed up. Overall by the criteria it is a 4. Although qualitatively I felt I was right on the edge of something much worse happening.

Runs 85 thru 88; P4/R17; HQR 3: Not as crisp and predictable as the baseline but very good. Overall a 3. HQR 3.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 89 thru 92; P4/R13; HQR 5: I could not achieve desired performance, and I had to work very hard just to get the adequate performance. I never really felt that controllability was an issue. Overall it falls somewhere in the 5 to 6 range. Settle for 5. I felt like I was on the edge of something much worse. I could work hard and make adequate even desired on one of the runs. HQR 5.

Runs 93 thru 97; P4/R16; HQR 4: I felt the roll response was more sluggish than I would like, although it was very predictable. HQR 4.

Runs 98 thru 102; P4/R8; HQR 3: The roll response was good although I didn't feel that it was quite as predictable as the baseline. Overall a 3. HQR 3

Runs 103 thru 107; P4/R15; HQR 6: The roll response was sluggish and unpredictable. I could achieve adequate performance pretty routinely. Overall a 5, it is a borderline 6. Pilot changed to HQR 6.

Date: 28 Feb. 1994; Pilot 6

Runs 1 & 2; P4/R2; HQR 2: I was able to get desired performance on both runs no problem. The configuration and roll went basically where I said it should go. Didn't have any overshoots that weren't mine anyway. I thought pilot compensation was not a factor for the performance, good. HQR 2.

Runs 3 thru 5; P4/R17; HQR 5: On three of those runs, most noticeably again in the far off heading cases where I had to get into roll rate quite a bit, I got adequate performance. Adequate performance was attained with a tolerable pilot workload. Deficiencies warrant improvement. Adequate performance requires considerable pilot compensation. HQR 5. It was worse than the last one, no matter what I did on the large cases I got into PIOs. I got a couple of overshoots that were just horrendous. But I got to adequate performance, if I remember right adequate is 4 out of 6. I tried on purpose to keep it as aggressive as I could as I have been taught. I got there but it was pretty objectionable. Worse in far off cases.

Runs 6 thru 8; P4/R1; HQR 4: I noticed though this was a pretty good configuration until I really got into it then I had trouble with PIOs on the larger offset cases to the point where I think it is not satisfactory without improvement. Deficiencies warrant improvement. Minor but annoying deficiencies. Desired performance requires moderate pilot compensation. HQR 4. It was very tempting to get out of the loop because I could easily correct the situation. But I stuck with what the Colonel taught me and said don't do that. You should go where I point it and it didn't at the end.

Runs 9 & 10; P4/R16; HQR 10: Adequate performance is not attainable with a tolerable pilot workload. It is not even controllable. The second I got out of the pitch axis, I had real problems. HQR 10.

Runs 11 thru 13; P4/R17; HQR 3: It is satisfactory without improvement. Some mildly unpleasant deficiencies. Minimal pilot compensation required for desired performance. HQR 3.

Runs 14 & 15; P4/R8; HQR 8: Adequate performance is not attainable with a tolerable pilot workload. Considerable pilot compensation is required for control. The times I was able to kill it, I was lucky. HQR 8.

Runs 16 & 17; P4/R1; HQR 2: Desired performance was easily attainable. Good—Negligible deficiencies. Pilot compensation not a factor for desired performance. HQR 2.

Runs 18 & 19; P4/R8; HQR 8: Adequate performance is not attainable with a tolerable pilot workload. Deficiencies require considerable pilot compensation for control. HQR 8. That pretty well sums it up especially when you start getting into the loop a lot. I couldn't stop it as I could with some of the previous configurations, got into overshoots, PIOs the whole thing was barely controllable.

Runs 20 & 21; P4/R7; HQR 10: It is not controllable if I stay in the loop. Adequate performance is not attainable with a tolerable pilot workload. HQR 10. I did the best when I wasn't touching the stick. When it popped up in front of me all I did was push the kill button that was about it.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 22 thru 24; P4/R17; HQR 4: Is it satisfactory without improvement? no. Deficiencies warrant improvement. Minor but annoying deficiencies. Desired performance requires moderate pilot compensation. Especially again with the cases that were way off central heading where I had to do a lot of rolling to get to them I noticed some oscillation, some PIOs, but it would stop. It was definitely controllable and I was able to get to the objective all the time, basically, except that I noticed the compensation that I had to use in order to get there. Leading things etc. When I got out into it on a neutral type of a basis, I started to PIO and oscillate all over the place. HQR 4.

Date: 28 Feb. 1994; Pilot 1 (LAMARS W/ Motion)

Runs 25 thru 28; P4/R1; HQR 2: Overall, achieved desired performance on all 4. I was able to hit the parameters very close with a little effort. Overall a 2. The motion, it doesn't feel like an airplane. It didn't effect it one way or the other.

Runs 29 thru 31; P4/R17; HQR 3: I felt the roll response wasn't quite as crisp and predictable as the previous configuration. Nonetheless, I achieved desired performance on all 4 runs with only a little increase in workload. Overall a HQR 3.

Runs 32 thru 35; P4/R16; HQR 4: I felt it was just a little bit laggy. It wasn't sluggish, it was just tougher to predict. Little bit of lag in the system, nevertheless I did achieve desired performance a number of times. Overall I would want that fixed. I will give it a 4. HQR 4.

Runs 36 thru 41; P4/R8; HQR 3: Very easy to fly. I achieved desired performance on all four. It seemed just a little bit less good than the baseline. HQR 3.

Runs 42 thru 45; P4/R7; HQR 4: I achieved desired performance on all 4, but I was working real hard to get it. On two accessions, on my initial bank maneuver the airplane over banked the way I wanted it to. The roll seemed crisp enough, but it didn't stop where I wanted. But, nonetheless, I did achieve desired performance, and never felt any problems with control. Small maneuvers were easy to do, overall a 4.

Runs 46 thru 49; P4/R6; HQR 8: Very sluggish, even difficult to control. On two of those runs I had to come out of the control loop and concentrate on maintaining control rather than the task. Sluggish makes it unacceptable. Overall an 8.

Runs 50 thru 54; P4/R11; HQR 2: The roll response is very crisp, very predictable, very similar to the baseline as near as I could tell. I achieved desired performance on all 4 runs with not much work on it at all. Overall a 2.

Runs 55 thru 58; P4/R15; HQR 9: Controllability was sometime in question. One run I hit desired, three times I didn't hit anything. I was barely able to maintain control. The key seemed to be as long as I made very small controlled inputs, it would fly okay, but as soon as I would make a big input it would go out of control. Overall a 9.

Runs 59 thru 63; P4+40/R1; HQR 2: Very crisp with very rapid response. At first it took a little bit of getting use too, but after the first run, I really liked it and I was always able to put it exactly where I wanted it. Even though it was very fast, the precision made up for any reason to downgrade it because of the fast response. Overall a 2.

Runs 1A thru 3A; P4/R1; HQR 2: No problems with controllability. I achieved desired performance on every run. Even though I made very aggressive control inputs I can just stick it wherever I wanted it and it felt really good. Overall HQR 2. The motions cues are better than the cues on the ground attack task. Feels more like an airplane, I don't feel the fade out as much as I felt it in the other one, although it was still there. I don't know if the motion adds anything but it doesn't seem to hurt it at this point. As far as the offset between the target and the TD box that doesn't seem to be a real factor either. Once you get used to going for the TD box it really doesn't effect the task at all. I will go with a 2 overall. Real nice flying configuration.

Runs 4A thru 6A; P4/R14; HQR 3: I rate it just slightly below the baseline system. Nothing I could put my finger on, but I just found myself having to work harder to get the desired performance, I couldn't quite stop it exactly where I wanted it. I did achieve desired performance on all the runs. Overall HQR 3.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 7A & 8A; P4/R16; HQR 7: Very poor system. Very hard to predict, tend to overshoot on virtually every maneuver I made. I could not achieve adequate performance with any consistency. Many times I would get into a damped PIO. It would damp itself out without me having to back off, in most. So overall a 7.

Runs 9A thru 11A; P4/R8; HQR 4: Overall not bad. I couldn't quite put it to where I wanted. Maybe a little sluggish in the response. I achieved desired performance rather consistently. It falls somewhere between 3 and 4. I am going with the 4. I would like to crisp up the roll response just a little bit.

Run 12A; P4/R15; HQR 9: Overall a terrible system. Very unpredictable as long as I stayed in loop with the task and in most cases I get a divergent roll PIO. Could not accomplish the task whatsoever, in any case. In a couple of the cases I had to completely come out of the task and just concentrate on maintaining level flight. Overall a 9.

Runs 13A & 14A; P4/R7; HQR 7: I felt like the roll-in was okay, felt crisp enough, but I just couldn't control it. I kept finding myself in oscillations, pretty much damped, but oscillating nonetheless. Overall I could not achieve adequate performance. Overshot on both cases 3 or 4 out of 6. Anytime I had to roll off axes I ended up overshooting. Overall a 7.

Runs 15A thru 17A; P4+40/R1; HQR 4: The roll response felt okay, it took me awhile to pick up on the fact that it was different in the pitch. I kept overshooting every so slightly. It seemed like the initial dig-in, as I pulled back on the stick was quite crisp and I would overshoot when I was trying to stop. Overall I could still achieve desired performance, but it was a little annoying. Overall a 4.

Runs 18A & 19A; P4+20/R1; HQR 9: It felt like severe rate limiting. I could eventually build up a good rate, build up slowly and then it was slow to stop. Made it very hard to control, very hard to predict, I found myself in severe PIOs due to the pitch. This is all in pitch not in roll. Overall I could not achieve adequate, because of the oscillations. HQR 9.

Runs 20A thru 22A; P4+80/R1; HQR 5: That's one of those hard to define cases. I achieved adequate performance, felt myself several times in very small amplitude oscillations, especially after a large input, as if the airplane was trying to catch some residual motion. It may have been residual motion from the simulator effecting it as well. Overall I could achieve adequate performance I just had to work at it. HQR 5. All comments were pitch.

<u>Date: 1 March 1994; Pilot 6 (LAMARS Fixed Base)</u>

Runs 1 thru 5; P4/R1; HQR 2: Numbers 1 thru 5, I felt even although I didn't attain performance from the outer right position that it was attainable with a little bit of practice. I did from the left out of position. All the other positions were no problem. Very easy, very controllable. Negligible deficiencies, if anything I'd complain about being a little bit too touchy in roll, little bit too sensitive, but I could achieve desired performance 3 out of 4 times therefore it is a 2.

Runs 6 thru 11; P4/R17; HQR 2: Very controllable. I achieved desired performance on 3 out of the 4 runs that I did attempt. But at the same time I felt that the roll rates were quite adequate I could roll the airplane when I wanted to, point it where I wanted. Negligible deficiencies. Pilot compensation not a factor for desired performance. HQR 2. One additional remark I think the roll in this one is less sensitive, I personally like it a little better, I can get use to this real easy.

Runs 12 thru 17; P4/R8; HQR 3: I was able to achieve desired performance again on 3 out of the 4 runs. Once I understood exactly how the roll axes was performing and for that reason I would say — Fair — Some mildly unpleasant deficiencies. Minimal pilot compensation required for desired performance. HQR 3. Basically, once I understood where to start rolling on the thing I could make desired performance easily. [Question: When you say you understood, were you ever able to figure out what you needed to put into?] That's correct, in this particular case *vs.* the last 2 configurations we ran, I basically didn't stop rolling. I rolled in and almost immediately rolled back out and that was the compensation that I had to put in, but there was plenty of time to do that, but if I was late at all I missed. The more I got into the control system the worse it got, so was I able to attain desired performance – yes, but it was lot a less flexible configuration. I didn't have extra time to get the task done.

Runs 18 thru 23; P4/R7; HQR 4: Correct me if I am wrong. I was able to attain desirable performance on 3 out of the 4 runs. [yes] — The only thing that I am worried on the criteria is no tendency for pitch or roll oscillations. There is definitely a tendency for roll oscillations, to overshoot desired bank angles and that gets back into how you adjust for descent into the box

so to speak. Is adequate performance attainable with a tolerable pilot workload? yes. Is it satisfactory without improvement? no. There are minor but annoying deficiencies. Desired performance requires moderate pilot compensation. I found myself thinking, stay out of the roll axis. It was like playing a one shot game, I got one shot, I didn't have any room to make any mistakes. If I got it right the first time I achieved desired performance, if I didn't get it right the first time the harder I got into the loop the worse it got and one time I didn't even get adequate when I was really into it real hard. So could I do the task? yes. Was it easy? no. I really had to compensate to get it there, but I could still get it there and it overshot in roll especially. HQR 4.

Runs 24 thru 27; P4/R16; HQR 5: Again early comments I had about getting in and getting out and one shot in order to accomplish the task is required even more so here in that I really wanted to stay out of the roll loop as much as possible and I am trying to get the maneuver completed farther and farther away from the runway. That is why you saw the adequate performance on the closer in tasks, the left and right inside, and the more I tried to get into the loop the worse it gets, so I try to get everything done before and as quickly as possible and fine tune toward the end of the task. I am making the altitude restrictions or the altitude limits on the task more nose down than I have in the past and that is a symptom, I think, of getting the task out of the way early and basically two stepping the maneuver, getting the lateral problem solved first and then getting the vertical problem solved right at the last minute. HQR 5.

Runs 28 thru 33; P4/R2; HQR 4: Deficiencies warrant improvement, it seems a little bit sluggish in roll to me, but other than that I can't determine exactly what I am doing to make the desired performance. I have been getting adequate and desired performance kind of things but it is always at the last minute again. I have to get the lateral out of the way early and the vertical out of the way as I can which is I had one going nose down pretty good to make the altitude restriction and it is kind of sloppy right at the end, so the desired performance requires moderate compensation. HQR 4.

Runs 34 thru 40; P4/R15; HQR 6: Adequate performance was attainable, but it was an intolerable pilot workload. Deficiencies require improvement. Major deficiencies. Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question. I really want to say 7, however, the results indicate that very objectionable but tolerable deficiencies. Adequate performance requires EXTENSIVE pilot compensation, [I would put extensive in capital letters]. I am putting so much lead in to get this task done, that is I can't really point it where I want it to go, I achieve adequate performance. I can say that 3 out of the 4 times I can achieve adequate performance according to the special occasions, but I really have to allow for the roll axis. The pitch is fine, in fact I am solving a lot of the task with pitch alone. In other words I get the bank out, bank in pull guess where I am going to start rolling the other way and then out of the pitch and back in on the pitch in order to complete the turn. According to the scale here I have to give it a 6, but I really want say something like 7. The more I get into the loop the more uncontrollable it gets. [Question: Are you moving toward a 6?] Moving towards the 6, but like I said, what I am basically grading here or telling you is with a lot of these grades is how much I am in the loop to complete the task.

Runs 41 thru 45; P4/R17; HQR 2: Is it satisfactory without improvement? yes. Good - Negligible deficiencies. Pilot compensation not a factor for desired performance. I had time left over, in fact I had to take out a whole lot of stuff that I was putting for some of the bad configurations in order to do the task. I had extra time. I felt that with a little bit of practice I could really achieve desired performance on a repetitive basis. HQR 2.

Runs 46 thru 49; P4/R3; HQR 8: Is adequate performance attainable with a tolerable pilot workload? no. Major discrepancies. Adequate performance is not attainable with a maximum tolerable pilot compensation. Controllability not in question, I would not say that. I go down lower and would say considerable pilot compensation is required for control. In order to do this task I think I am down to a 8 because this is worse case than before. If I stay out of the loop I am fine, then if I even touch the stick I am in trouble. The times that I got adequate performance out of that configuration were just flukes I felt. I had trouble maintaining control to do anything other than fly straight and level. HQR 8.

Runs 50 thru 54; P4/R11; HQR 1: This is a 1, extremely highly desirable. I have time to make mistakes and correct them. I have time put the airplane where I want it coming over the threshold. My ability not to perform is my problem not the airplanes problem, as I said before if I wanted to pick an airplane to fly for this particular task, this would be it. HQR 1.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Date: 1 March 1994; Pilot 5 (LAMARS Fixed Base)

Runs 1B & 2B; P4/R1; HQR 3: It felt like pulling up in pitch was no problem, I had really good response there. Like the majority of the targets were up in pitch just slightly 30°-40° off, there were a couple that were lateral. The lateral targets when I pulled towards those I did have some overshoot usually not worse than one overshoot. There was one time when I overshot, but I tried to over compensate and another overshot out of that. It was still the one overshoot primarily. It is definitely satisfactory as far as some improvement. As far as I can feel here it felt like it was fair with some mildly unpleasant deficiencies and that was primarily one overshoot on the lateral side. HQR 3.

Runs 3B thru 5B; P4/R17; HQR 4: I felt like most cases it was one overshoot. This is pretty much the roll axes we are looking at is it? [yes] Okay. I would say that it is satisfactory with some improvements. I would say it is a little bit more annoying deficiencies out of this one than there was in the last roll. Tend to come into the overshoot a little bit more. HQR 4.

Runs 6B & 7B; P4/R8; HQR 2.5: On this one I felt really comfortable with it. Really saw maybe one overshoot, it seemed like the second part, the second run I did on this configuration, it seemed like most of the targets were more closer in pitch than they were in lateral so I didn't feel I excited the system. Everything is satisfactory to me. Some mildly unpleasant deficiencies, but between good [you can't do a 2½ can you? yes as long as it is not 3½ or 6½. It is up to you.] HQR 2½. The mildly unpleasant tendency was on the first run of this configuration, on one of the runs I tend to overshoot just slightly and that was me trying to rate the aircraft over to the air and then bumping it back unloading it when I did that I had to compensate a little bit. So that was the mildly unpleasant. It felt pretty good configuration to me. I personally never give a Cooper-Harper 1, maybe we should re-evaluate this, but to me that is like the perfect system.

Runs 8B thru 10B; P4/R7; HQR 5: This one was sloppier than what I have seen, however, I was able to complete the task. Needs a little bit of improvement. Some deficiencies in that I got an overshoot close to time, just one overshoot, sometimes I got 2. Some what objectionable in rolling back and forth especially on the large lateral movements in trying to compensate. HQR 5.

Runs 11 thru 13; P4/R16; HQR 4.5: I was able to accomplish the task. Desired performance was there. I noticed some of them required somewhat more pilot workload on a couple of them, the lateral ones. The pitch ones were no problem. More pilot workload, probably in between minor and moderately objectionable. HQR 4.5.

Runs 14 & 15; P4/R2; HQR 2.5: Definitely got everything within desired performance. Not too much by way of overshoot, everything felt comfortable on this. Minor, negligible discrepancies. HQR 2.5.

Runs 16 thru 18; P4/R15; HQR 7: We only missed one target out of all of those. Had about two overshoots on a lot of them. One time I had some pitch and roll oscillations, was able to correct those. It was more the overshoot controlling those. Adequate performance, we had some deficiencies. HQR 7.

Runs 19 thru 21; P4/R17; HQR 7: Was able to get desired performance out of a number of kills. Most of the times there were one to two overshoots. HQR 6. [Question: You did get desired performance?] I am kind of trailing the ragged edge I got all of the kills there, it seemed like one overshoot. Once or twice I got 2 overshoots. Because it is right on the edge of adequate, I can't give it a 6½ I will have to give it a 7. I did fly a little bit better than the last one.

Runs 22 thru 24; P4/R6; HQR 10: Barely attained adequate performance. Major deficiencies. It is uncontrollable because I kept getting some pitch oscillations in there that sometimes I couldn't control even if I went hard and aggressive. If I went easy, then ease it in there, I could usually get some major deficiencies, but when I really tried to rate it in there, I just ended up with PIO. HQR 10.

Runs 25 & 26; P4/R8; HQR 2.5: It felt pretty adequate, definitely it was in the desired performance. Fair, not too bad handling qualities, negligible deficiencies. HQR 2.5.

Runs 27 & 28; P4/R17; HQR 2.5: Definitely had desired performance on this. Satisfactory, some unpleasant deficiencies. HQR 2.5. No difference on this one and the previous one.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 29B & 30B; P4/R11; HQR 3: I hit the desired performance, that was not a problem. The aircraft flew fairly well in roll, however, I didn't feel like I had quite the same response available to me that I had on the previous two, but it was still in the desired criteria. HQR 3.

Runs 31B & 32B; P4/R14; HQR 5.5: I got all the kills but fell under the adequate performance, because I ended up having 2 overshoots several times in there. Moderately objectionable deficiencies because of that. HQR 5.5.

Runs 34B & 35B; P4/R5; HQR 8: The performance was less than adequate. It seemed to me that had many overshoots. The response time seemed like it was real quick. I put in an input, it would tend to cause me to overshoot a lot. It was very difficult to get it tracking to where I wanted it. HQR 8.

NOTE: Stick gain was not adjusted for this high control power case.

Runs 36B & 37B; P4/R3; HQR 9: I didn't have any overshoots, the thing was I had very slow roll response and when I pull slow to it, I didn't get the response I wanted, then if I over corrected it then I definitely didn't have enough response in trying to correct back. This didn't even hit the adequate in my opinion. HQR 9.

Date: 1 March; Pilot 5 (LAMARS Fixed Base)

Runs 38 & 39; P4/R5; HQR 4: I got desired performance, easily right on the edge of that, in fact some times it hit adequate. The overall performance was not desired, it was adequate. I was able to point and roll just about what I needed to, it felt like the roll rate was just a little slow. I was able to accomplish the adequate task but could not quite get the roll rates that I wanted. HQR 4.

Runs 40 & 41; P4/P17; HQR 3: I was able to accomplish everything as desired, within one overshoot. However, it felt like roll response could be just a little bit quicker. HQR 3.

Runs 42 thru 44; P4/R10; HQR 7: I was able to get all the targets, but I ended up many times with more than two overshoots, so we were just under adequate performance. Major deficiencies. HQR 7.

Run 45; P4/R6; HQR 9: I did not get adequate performance. Major deficiencies. Lots of PIO. HQR 9.

NOTE: This run was discounted

Date: 2 March 1994; Pilot 5

Runs 1 & 2; P4/R2; HQR 3: Was able to hit the desired criteria. It was satisfactory without improvement. Fair, some mildly unpleasant deficiencies. It felt like the roll response was a little bit sluggish. I would like to have quicker roll response. Kind of increased my pilot workload, kind of wait on it and get over there. HQR 3.

Runs 3 & 4; P4/R17; HQR 2: Was within the desired performance. It was satisfactory without improvements. Good, negligible deficiencies. Primarily just a little lag on the roll but not too much. It was real easy to track. HQR 2.

Runs 5 & 6; P4/R8; HQR 2: Was definitely within desired performance. It was satisfactory without improvements. Good, negligible deficiencies. HQR 2. [Question: Did you feel the same little lag and roll as in the previous?] Yes about same as last one.

Runs 7 & 8; P4/R7; HQR 3: Met the desired criteria. I had no more than one overshoot. Fair, some mildly unpleasant deficiencies. I had almost an overshoot on some of them. HQR 3.

Runs 9 & 10; P4/R6; HQR 6: Adequate performance in most cases, it was not satisfactory. There are some major deficiencies that warrant improvement. It was very objectionable, however, I felt that if I increased the pilot workload I was able to track onto the task. Adequate performance requires extensive pilot compensation. HQR 6.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 11 & 12; P4/R1; HQR 3: It was satisfactory without improvements. That was because I was able to hit all the desired tasks. However, I thought it fair, some mildly unpleasant deficiencies. And again it seemed like there was just a little bit of lag in the roll. I had to do a little bit of pilot compensation on the initial gross acquisition to get the aircraft to where I wanted it positioned. HQR 3. [Question: So you thought you needed a little bit of lead to get to stop where you wanted it to?] Yes, a little bit.

Runs 13 thru 15; P4/R16; HQR 2: It was satisfactory without improvements. Not too much pilot compensation required for the desired performance. HQR 2.

Runs 16 & 17; P4/R15; HQR 5.5: Major deficiencies. If I was very smooth and didn't put large inputs in and tried to command large roll rates I was able to get over and track, but if I commanded large roll rate then the aircraft wouldn't respond appropriately. Considerable amount of pilot workload in doing that. Debating if adequate or not. In most cases it was adequate, but major deficiencies, very objectionable with pilot compensation. I could make it work. HQR 5.5.

Runs 18 thru 20; P4/R5; HQR 4: Felt like it took moderate pilot compensation in order to control it. HQR 4. The roll rate was not quite right, was not responding the way I felt it should. It seemed like I was compensating for that continuously. I can't really put my finger on it.

Runs 21 & 22; P4/R3; HQR 7: Considerable pilot workload was required, however, I was able to perform a lot of the tasks. It took a lot of pilot compensation but the airplane was still controllable. HQR 7.

Runs 23 & 24; P4/R10; HQR 5: Adequate performance required considerable pilot compensation, because I was always trying to recorrect back. There were lots of overshoots. HQR 5.

Runs 25 & 26; P4/R9; HQR 7: Could not get adequate performance. I would end up with a lot of overshoots. Major deficiencies. Adequate performance not attainable with maximum tolerable pilot compensation because of all the overshoots I was getting. HQR 7.

Runs 27 & 28; P4/R16; HQR 4: It seemed like we were just outside the edge of desired performance, because I had some overshoots there a few times outside the criteria. It took a little more pilot compensation in order to do the fine tuning, at least the last part of the gross acquisition task. HQR 4.

Runs 29 & 30; P4/R13; HQR 4: I did not quite get desired performance because of the fact that I kept getting some overshoots in there, seemed like this system was kind of jerky. Deficiencies warrant improvement. However, they were minor but annoying deficiencies. Desired performance requires moderate pilot compensation and I was able to work through that. HQR 4. Just below desired because of the overshoots. It was adequate. I was able to get all six targets. Main objection is overshoots.

Run 31; P4/R12; HQR 9: Bordering right on the edge of controllable. If I do very minor inputs I can control it. So I am going to say yes, it is controllable, however it does not meet adequate performance. Has major deficiencies. Intense pilot compensation is required to retain control. If you put too large of an input in you are really fighting to maintain control, so you really have to watch what you are doing. HQR 9.

Runs 32 thru 34; P4/R1; HQR 4.5: We were just under the desired performance, there were couple of overshoots there, compensation required on this, it is not satisfactory. Deficiencies were pretty much in between minor and moderately objectionable deficiencies. HQR 4.5

Runs 34 thru 40; P4/R2; HQR 4: Basically met the desired in most cases. There was one where we were adequate, we got the 3 out of 4. It did require some moderate pilot compensation even though it was desired performance. HQR 4.

Runs 41 thru 46; P4/R17; HQR 3: It seemed to me that this one met all the desired criteria after we looked at it again. Satisfactory without improvements. However, mildly unpleasant discrepancies. Pilot compensation required for desired performance. HQR 3. [Question: Was there any particular thing that caused the pilot compensation to go up there?] It was in game trying to correct back for any runway overshoot.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 47 thru 50; P4/R17; HQR 4: This one we was in desired performance. However, I did feel that there were some discrepancies that warrant improvement. Workload was moderate pilot compensation required. HQR 4. The end game seemed like it didn't have enough roll authority at times to get me back to where I needed.

Runs 51 thru 55; P4/R15; HQR 4: This appeared that it meant all the desired criteria. However, again I felt that the pilot compensation end game required a little bit of work so there were some deficiencies there so I am going to rate this a 4. It seemed to me it took longer for the effects to take place. HQR 4.

Runs 56 thru 60; P4/R8; HQR 2.5: It seemed to me like it meant desired criteria. Repeated one run, didn't feel too comfortable with it. I repeated it and felt fine, satisfactory without improvement. Fair, some minimal pilot compensation required for the desired performance. HQR 2.5.

Runs 61 thru 67; P4/R7; HQR 5: On this one we were able to meet the desired criteria most of the time, however, I found that if I did a large input initially in some cases it required considerable pilot compensation. Because of that fact initial input required a lot of pilot compensation, then from there it flies pretty smooth, so I am going to give it a 5. HQR 5.

Runs 68 thru 72; P4/R6; HQR 7: I didn't feel that I had adequate performance with a tolerable workload, deficiencies require improvement, feel that there are major deficiencies. Adequate performance was not attainable with maximum tolerable pilot compensation in most cases, however, the aircraft was controllable. HQR 7.

Runs 73 thru 76; P4/R10; HQR 3: Was satisfactory without improvement. I felt that it was pretty good handling qualities, negligible deficiencies. However, I did have to put some pilot compensation in. HQR 3.

Runs 77 thru 81; P4/R11; HQR 3: Seems to me it met all the desired criteria in most cases even after repeating. Seem like it responded real quick in some of the things that I was doing. End up having to do some pilot compensation, but still felt pretty comfortable. HQR 3.

Runs 82 thru 85; P4/R14; HQR 6: We had adequate performance most of the time, however, to get the adequate performance, of course it wasn't satisfactory. Very objectionable. Somewhat tolerable deficiencies. Adequate required excessive pilot compensation. HQR 6.

Runs 86 thru 89; P4/R13; HQR 6: I was able to get adequate performance in most cases, but right on the edge. I felt it was objectionable but tolerable and it required extensive pilot compensation. It just seemed like I put an input in and I had a tendency for PIO. HQR 6.

Runs 90 thru 93; P4/R12; HQR 10: Performance was adequate, somewhat tolerable workload, however, big time deficiencies. Intense pilot compensation normally, and other times it would loose control. Improvement are mandatory on this one, because control will be lost during some portion of the required operations. HQR 10.

Runs 94 thru 98; P4/R10; HQR 2.5: Every now and then some mildly unpleasant deficiencies. HQR 2.5.

Runs 99 thru 102; P4/R1; HQR 2.5: Satisfactory without improvement. Between good and fair, there was some pilot compensation required but not much. HQR 2.5.

Runs 103 thru 107; P4/R16; HQR 3: Satisfactory without improvement. Felt like I had a little bit more compensation required than I did before. HQR 3, with some pilot compensation required.

Runs 108 thru 112; P4/R15; HQR 8: Usually I got adequate performance. However, at times considerable pilot compensation required for control. If I didn't do large inputs or very small inputs it would stay within adequate range, however occasional considerable pilot input just to maintain control. HQR 8.

Runs 114 thru 117; P4/R9; HQR 4.5: I was able to get adequate performance most of the time, however, it was not satisfactory. There are deficiencies, the deficiencies to me were moderately objectionable. At times there was between moderate and considerable pilot compensation. HQR 4.5.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 118 thru 121; P4/R10; HQR 2: Is satisfactory without improvement. Pilot compensation not a factor for desired performance. HQR 2.

Runs 122 thru 125; P4/R3; HQR 7: Was not able to meet adequate performance. Major deficiencies. I could not get performance even with maximum pilot compensation, however, the aircraft was always controllable. HQR 7.

Runs 126 thru 130; Pr/R2; HQR 2: It was satisfactory without compensation. Negligible compensation required on my part. HQR 2.

Runs 131 & 132; P4/R17; HQR 3: Was able to meet all the desired criteria with just a little bit of overshoot usually no more than one. Minimal pilot compensation required for desired performance. HQR 3.

Runs 133 & 134; P4/R1; HQR 2.5: It is satisfactory without improvement. Minimal pilot compensation required, but actually a little bit less than. HQR 2.5. A little better than the previous one.

Runs 135 & 136; P4+80/R1; HQR 3: Satisfactory without improvement. However I felt that pitch response was a little sloppy, not very much by way of overshoots, but could have a quicker response on the pitch. Roll felt comfortable. HQR 3. Primarily because of pitch.

Runs 137 & 138; P4/+40/R1; HQR 2.5: Able to get desired performance. Satisfactory without improvement. Felt to me like the response was pretty good, a little bit better than the last one. HQR 2.5

Runs 139 & 140; P4+20/R1; HQR 4: I don't felt like I had desired performance, because there were some pitch overshoots and I felt like the pitch was lagging. Some improvements needed. There are some deficiencies. Also felt to me like moderate pilot compensation was required because of the slow lag in the pitch. HQR 4.

Runs 141 & 142; P4/+40/R9; HQR 2: Desired criteria. Satisfactory without improvements. Able to put much pitch point where I needed to and roll response felt pretty good. HQR 2.

Runs 143 & 144; P4+80/R1; HQR 3: This one seem liked the performance was satisfactory. Fair, some flying qualities were not that great, some pitch in the roll. Minimal pilot compensation required for desired performance. HQR 3.

Runs 145 & 146; P4+80/R7; HQR 4.5: I felt that I didn't quite get desired performance. Adequate performance was achieved. There were some deficiencies. Desired performance requires moderate to considerable pilot compensation for large abrupt inputs. HQR 4.5. Problem with roll axis. Pitch felt fine.

Runs 147 & 148; P4+40/R7; HQR 5: I felt that I didn't get desired performance. I did get adequate performance in most cases. Moderately objectionable deficiencies. Considerable compensation required in the lateral axis. HQR 5.

Runs 149 & 150; P4+20/R6; HQR 7: I didn't quite get adequate performance, because of the amount of overshoots that I had. Deficiencies require improvement. Major deficiencies. However, I could always control the airplane. It seemed like a slow response in pitch. Very bad lateral response. HQR 7. Overshoots in both axes.

Runs 151 & 152; P4/R2; HQR 3: On this I felt I easily had desired performance. Minimal pilot compensation required for desired performance. HQR 3.

Runs 153 & 154; P3/R2; HQR 5: I didn't have desired performance. Most cases I had adequate performance. Deficiencies warrant improvement. These deficiencies were primarily in the pitch axis. Required moderate pilot compensation to get the adequate performance. HQR 5. Pitch axis required more compensation.

Runs 155 & 156; P4+20/R1; HQR 5: I didn't feel like I got quite the desired performance due to pitch response and some lateral response, so it requires some improvement. Adequate performance requires considerable pilot compensation. HQR 5. I thought that it was a little bit worse than the last one. Very slow like it lagged.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Date 3 March 1991; Pilot 7

Runs 2, 3 & 4; P4/R2; HQR 4: Desired performance requires moderate pilot compensation. The reason is roll. It was slightly sloppy and there was a slight tendency for me to get into a PIO although it was very minor.

Runs 5, thru 7; P4/R17; HQR 3: It is satisfactory without improvement. I did have to compensate, there was just a minor tendency, a very slight tendency, to get into a PIO, but it was extremely minor and correctable. HQR 3.

Runs 8 thru 11; P4/R8; HQR 4: I had to run 4 times and the reason is I wanted to see what my workload was, and it was definitely higher than I wanted it to be. I could correct, but it was higher than I wanted. HQR 4.

Runs 12 & 13; P4/R16; HQR 5: I noticed that I overshot on several occasions. I was able to compensate sufficiently to engage all targets. The tendency to PIO was not excessive, however, I think the roll rate was a little on the slow side. HQR 5.

Runs 14 thru 16; P4/R15; HQR 7.5: Is adequate performance attainable with a tolerable pilot workload? definitely not. Deficiencies require improvement. Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question. HQR 7. Twice it went into PIO in which it wasn't doing exactly what I wanted it to, however it was fully recoverable. HQR 7.5. If you got the roll rate up and you wanted to reverse it, it did not respond very quickly to stopping the roll rate. It actually continued to roll in the other directions for periods of time while you were putting opposite roll in.

Runs 17 thru 20; P4/R11; HQR 4.5: Is it satisfactory without improvement? no. Having trouble trying to decide whether the deficiencies are minor but annoying, or moderately objectionable. Performance requires moderate pilot compensation, I think that is probably true. Considerable pilot compensation that's where I am. So, I am going to compromise and call it HQR 4.5.

Runs 21 thru 23; P4/R1; HQR 3: I only noticed one overshoot and that was due to over aggressive maneuver. One of the things I noticed on this one, even if I was slightly off, the aircraft was forgiving it allowed me to compensate and reacquire. HQR 3.

Runs 24 thru 26; P4/R6; HQR 7: There are some deficiencies, they are not extreme. It requires moderate pilot compensation. HQR 4. It wasn't extremely forgiving and, on the other hand, it wasn't unforgiving either.

Runs 27 & 28; P4/R7; HQR 5: Some mildly objectionable deficiencies for sure. To get out of it, performance requires considerable pilot compensation. However, adequate performance can be attained. HQR 5.

Runs 29 thru 31; P4/R6; HQR 7: Is adequate performance attainable with a tolerable pilot workload? no. Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question. HQR 7.

Runs 32 thru 34; P4/R2; HQR 4: What I noticed is as long as I don't get really aggressive it doesn't have any real problems, but when I start getting really aggressive it isn't forgiving. It definitely does require some pilot compensation. HQR 4.

Runs 35 thru 37; P4/R10; HQR 5.5: HQR 5.5. Reason, I am torn between whether it is considerable pilot compensation and extensive pilot compensation.

Date: 3 March 1994; Pilot 2:

Runs 38 & 39; P4/R2; HQR 3: Is it controllable? yes. Adequate performance attainable all the time. Desired performance was attainable all but one time. Really no problems with over compensating it. I was able to get a 3 for all the runs except for one and that one time it was probably a 5 where I had the two overshoots. One out of the ten times was a 5 the other times was a 3. Must give it an overall rating. HQR 3.

Runs 40 thru 41; P4/R17; HQR 3: Always controllable. Adequate performance attainable, desired performance attainable. HQR 3 overall. Seemed to be slightly heavier in roll than the previous configuration.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 42 & 43; P4/R8; HQR 2: In general sometimes pitch overshoots more than roll overshoots. Definitely not as heavy as previously. I liked it a lot. HQR 2 overall rating.

Runs 44 thru 46; P4/R7; HQR 3: Always controllable. Adequate performance attainable all the time. It is at the desirable level. HQR 3 overall, there is some mild deficiencies, seemed slightly heavier than the previous configuration in roll. [Question: Do you think you maintained the same level of aggressiveness as you did with the previous one?] I compensated slightly by being a little bit less aggressive on this configuration, because of the heaviness in the roll, because of the delay in the response with the airplane. If you were as aggressive, you tend to overshoot more.

Runs 47 & 48; P4/R16; HQR 2: It is controllable. Adequate performance always available. Desired tolerance is available. Had one overshoot occasionally. HQR 2 overall. There are very fine differences between these it seems.

Runs 49 & 50; P4/R11; HQR 3: On 49 and 50 very fine differences between the previous ones. It is controllable. Adequate performance is always available. Desired performance is available. Seems slightly heavier roll. HQR 3 overall.

Runs 51 & 52; P4/R6; HQR 6: It is controllable. Adequate performance is generally available. Desired performance is available, but only with great compensation. HQR 6 overall. The aileron response is significantly worse than the previous runs we've had. Therefore the roll efforts are high. The roll response is slow enough that you are forced to grossly compensate in it. It precludes being aggressive. If you are aggressive then you will run out of time before you end up being able to get the shot off.

Runs 53 thru 55; P4/R16; HQR 4: It was controllable at all times. Adequate performance is available. Generally desired performance is available. I didn't like it as much as some of the more lively ones. However, it was better than the previous one with a very slow roll response. You could probable quantify the time first acquisition and the time that it took to get the shot away on that it seemed like it took a longer for both than it has on some of the more lively ones. HQR 4 overall.

Runs 56 & 57; P4/R1; HQR 4: It was always controllable. Adequate performance was available at all times. Desired performance was available most of the time. One time I was unable to get it within the time. As far as roll response, it seem pretty nominal for what we have been seeing, somewhere in the middle of the road of what we have been seeing. It seemed like there was significant disparity in the control harmonizations. HQR 4 overall. [Question: You said disparity, what one was too sensitive?] Between pitch and roll there was a more noticeable disparity between the two. My overshoots were typically pitch and roll. I could afford to be more aggressive with the roll than I could with the pitch because it is more sensitive in pitch than in roll.

Runs 58 & 59; P4/R8; HQR 2: This one worked out pretty well. The harmony was greatly improved. It is controllable. Adequate performance is attainable and I think we were largely meeting the desired performance. HQR 2.

Runs 60 & 61; P4/R15; HQR 6: Performance is more difficult. Significantly less responsive than the last time. Initiating roll input tends to have a significant lag, at least two occasions where I was unable to get the shot off. HQR 6 overall.

Runs 62 & 63; P4/R7; HQR 2: It is controllable. Adequate, yes. Desirable, yes. I like this probably if not the best, the best one I have seen so far. HQR 2 overall, I had no problems whatsoever. I could do whatever I wanted without concern of the control system.

Runs 64 & 65; P4/R10; HQR 5.5: It is controllable. Adequate performance is generally available. Desirable not as often. It is between a 5 and 6 overall. I get much heavier, it is impossible to stay as aggressive. Heavy is the wrong word, it is much less responsive. It is impossible to stay as aggressive as I was in previous modes. Has overshoot tendency.

Runs 66 & 67; P4/R14; HQR 9: Generally controllable, but sometimes if you stay aggressive it essentially gets into a PIO. Adequate performance is sometimes available. Desired performance is seldom available. HQR 9.

Runs 68 & 69; P4/R6; HQR 5: It was controllable. Adequate performance was generally available. HQR 5. Looked pretty good compared to the previous one. Still had some difficulties in the lagging response.

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

Runs 70 & 71; P4/R1; HQR 2: Negligible deficiencies, I could get the shot away in about the same time that I am just getting first time acquisition with the previous configuration. Even the one before that actually. HQR 2.

Runs 72 & 73; P4/R8; HQR 2: It is controllable. Adequate and desirable are all good. HQR 2 overall, I had no problems.

Runs 74 thru 76; P4/R15; HQR 6: It was controllable generally. Sometimes there was diversion. Roll PIOs. Generally adequate performance, desirable performance often wasn't much more objectionable. In the roll had to work a lot harder to achieve the performance and it precluded to be as aggressive as others allowed. HQR 6.

Runs 77 & 78; P4/R7; HQR 3: It is controllable. Adequate performance is attainable. It is generally satisfactory. HQR 3.

Runs 79 & 80; P4/R10; HQR 2: It was controllable. Adequate performance is available. Largely satisfactory. HQR 2 overall. Pretty good I didn't have any problems.

Runs 81 & 82; P4/R14; HQR 5: Generally controllable. Often a tendency towards a roll PIO. You have to try and get out of phase with it instead of just reacting which makes it worse. Adequate performance is, I guess I got adequate all the time, I got desired all the time as far as that goes, but it was with some pretty significant amount of work. Overall a HQR 5.

Runs 83 & 84; PR/R16; HQR 4: It is controllable. Adequate performance is attainable. Desirable performance I think was good no overshoots outside, I might have had one overshoot. I got all the shots off. HQR 4. overall.

Runs 85 & 86; P4/R17; HQR 3: It is controllable. Adequate performance was attainable. Got all the shots, satisfactory. Desirable performance attainable. HQR 3 overall. I couldn't be quite as aggressive as I would have liked to have been because it seemed like damping more than anything else. It's not inside a PIO. It's like the response was mushy.

Runs 87 & 88; P4/R13; HQR 7: Largely controllable. Adequate performance was pretty much attainable. Did not get desirable. HQR 7. PIO tendency, you have to think about getting out of phase with it to stop the PIO.

Runs 89 & 90; P4/R12; HQR 10: It is not controllable. It is a Cooper-Harper 10. Control was often lost. If I was able to get the shot it was just blind luck, because he happened to be in front of me and I didn't have to roll very much. HQR 10.

Runs 91 & 92; P4/R11; HQR 4: It was generally controllable. Performance was adequate, I believe I got all the shots off so it was even desirable. It was not as crisply responsive as I would have hoped. HQR 4.

Runs 93 & 94; P4/R9; HQR 6: Runs 93 and 94 were generally controllable. It was adequate performance. I missed desired performance at least one time or perhaps two. I didn't even get a shot off one time and that was a 6 Cooper-Harper overall, because of the tendency to excite a roll PIO, when you do gross or aggressive roll correction movements.

Date: 4 March 1994; Pilot 7

Runs 1 thru 3; P4/R17; HQR 5: It is not satisfactory without improvement. The deficiencies are minor. It takes moderate pilot compensation. HQR 4.

Runs 4 & 5; P4/R14; HQR 6: It is not satisfactory without improvement. It is a little more difficult than the previous run. The objections, you can correct them with considerable pilot compensation. HQR 5.

Runs 6 & 7; P4/R14; HQR 6: It is not satisfactory without improvement. It is slightly worse than the last run. Adequate performance requires extensive pilot compensation. Not very forgiving, there is a tendency if you are aggressive to get into a PIO. It seems like there is a delayed reaction. You put in an input and initially the roll rate doesn't come up then all of a sudden you get a very rapid roll onset that you have to compensate for. HQR 6.

Runs 8 thru 10; P4/R13; HQR 7: The question, is adequate performance attainable with a tolerable pilot workload? I was able to obtain adequate performance in that I got all the targets. I only missed one out of the 3 sets that were run, however, it is sort of borderline in that case, but it certainly is not satisfactory without improvement. Deficiencies are very objectionable. Whether

they are tolerable or not, it is very difficult for me to ascertain here, but it does require extensive pilot compensation. It was slightly worse than the previous run. I would say it is probably a 7, adequate performance is not really attainable with maximum pilot compensation, but the controllability is not in question. HQR 7.

Runs 11 & 12; P4/R12; HQR 8: Performance is definitely not adequate. It is not attainable with a tolerable pilot workload. It is more difficult than the last run which I rated as a 7. It takes actually considerable pilot workload to maintain control and aggressive maneuvering. I think I will rate that one an 8.

Runs 13 thru 15; P4/R17; HQR 4.5: It is not satisfactory without improvement. Deficiencies run between minor but annoying to moderately objectionable. When you look at the demand on the pilot it does require for sure moderate compensation. HQR 4.5.

Runs 16 & 17; P4/R5; HQR 4: HQR 4. [Question: Did you see any differences between this one and the previous one?] Yes, this one was just a slight bit easier. Definitely there was no doubt in my mind that it was not satisfactory without improvement. This one depending on how aggressive you are there is a possibility that you can let it slide without improving, but overall you don't want a fighter airplane to do this particular task that way.

Runs 18 thru 20; P4/R9; HQR 5.5: It borders between being moderately objectionable and very objectionable but tolerable deficiencies. Depending on how aggressive you are, it requires either considerable or extensive pilot compensation. One of the things I noticed was that it doesn't do anything really weird; that is, it is predictable and if you lead your roll out you can compensate for it. HQR 5.5.

Runs 21 & 22; P4/R3; HQR 7: I don't believe adequate performance is attainable with a tolerable pilot workload. The big problem with this one is not controllability so much. It doesn't do any thing crazy, but it just feels like a tanker, it is extremely slow roll rate. HQR 7.

Runs 23 & 24; P4/R1; HQR 4: Actually, this one was not too bad, but for some reason I don't think it is satisfactory without improvement. The deficiencies are really minor and it only requires moderate pilot compensation, but there is something about it I don't know if it is just the initial input, whether the roll rate, whether there is a significant difference in the initial roll rate *vs.* what you end up with. HQR 4. It is not a bad model but it is not satisfactory without improvement.

Runs 25 & 26; P4/R17; HQR 3: This one is satisfactory without improvement. There are some mild deficiencies that requires some compensation, however, this one I rate as a 3, because it is satisfactory without improvement. It is definitely not a 1 or 2. HQR 3.

Runs 27 thru 29; P4/R1; HQR 4: This one is border line but I don't think it is satisfactory without improvement. I notice that the pitch was a little more sluggish than the previous runs that I have flown. Desired performance requires moderate pilot compensation. It wasn't considerable pilot compensation. HQR 4.

Runs 30 & 31; P4/R17; HQR 4: Not much difference between this one and the last one. I think if anything it was slightly more difficult, however I am going to have to rate it the same. HQR 4 describes this one, but if anything subjectively it might be a little bit more difficult than the previous run.

Runs 32 & 33; P4/+80/R1; HQR 3: HQR 3. The pitch seemed a little bit sluggish, the roll was pretty good. Overall it was satisfactory.

Runs 34 thru 37; P4+40/R1; HQR 4: Comparison to the last run, I think it is slightly degraded. It is borderline between satisfactory without improvement. The deficiencies are minor and it does require some pilot compensation. It really is not that bad, I thought that it was slightly degraded form the previous one, slightly degraded in the roll as well as being very similar in the pitch. HQR 4.

Runs 38 & 40; P4+20/R1 HQR 4: Overall pretty good model, along the same lines as the last one. I don't think it's satisfactory without improvement. There are minor deficiencies which are annoying but with moderate pilot compensation you can get the mission done. I think there was a combination, it seemed to me if I was really quick in the pitch, I got into a pitch overshoot

which I hadn't experienced before. But initially I think the onset was actually slow on the pitch, but it accelerated quickly and if you quickly apply the pitch that you wanted to and then backed off right away you were able to compensate for it. HQR 4.

Runs 41 & 42; P4/R1; HQR 3: Again this was another borderline one as far as satisfactory without improvement. I am going to say yes it is, there was some mildly unpleasant deficiencies. But they are difficult to verbalize. There were some minimal compensation required to deliver performance. HQR 3.

Runs 43 & 44; P3/R1; HQR 4: I don't think this is satisfactory without improvement. The deficiencies are between minor and moderately objectionable. Leaning toward the minor objectionable. There is some moderate pilot compensation required. The nose basically doesn't stay where you put it. I will rate it a 4 because of that. HQR 4.

Date: 4 March 1994; Pilot 2

Runs 45 & 46; P4/R17; HQR 2: Desired performance was attainable all the time. I had one overshoot once. HQR 2.

Runs 47 & 48; P4/R8; HQR 3: Desired performance is available seems like all the time. I didn't have the particular difficulties, it seemed somewhat heavy in roll, but perhaps a slight bit more delay, but certainly not compensating starting any PIOs or anything like that. I give it a 3. HQR 3.

Runs 49 & 50; P4/R15; HQR 5: It is controllable. Adequate performance is available. Desired performance is more difficult. If you keep the same level of aggressiveness, then you will overshoot and have a great deal of difficulty acquiring the task, but if you smooth out, try and be a lot smoother, you can acquire it. Overall a HQR 5.

Runs 51 & 52; P4/R6; HQR 4: It is controllable. Adequate performance is attainable with a tolerable workload. Desired performance is more difficult. It seems sluggish, as far as the roll rates are concerned I will give it a 4. HQR 4.

Runs 53 & 54; P4/R5; HQR 2: It is controllable. Adequate and desired performance were both attainable. I thought it was pretty good. It seemed like it was pretty nimble both in roll and in pitch. Negligible deficiencies. Overall a HQR 2.

Runs 55 & 56; P4/R3; HQR 8: It is controllable. Adequate performance was not attainable and definitely not desirable. It doesn't seem to want to depart in flight or anything like that, so it doesn't really PIO. It is so sluggish as to respond inadequately. You have to compensate by using pitch to get the target. If someone flies in front of them, you might be lucky, but otherwise you are not going to maneuver to get it on there. HQR 8.

Runs 57 & 58; P3/R1; HQR 4: It is controllable. Adequate performance is always available, and desirable performance is largely available, it seemed like it was more responsive in roll than in pitch. Felt like I was flying it through a marshmallow or something. HQR 4. Especially the pitch, roll seemed okay.

Runs 59 & 60; P4/R1; HQR 2: I liked it a lot, it seemed like it was more suitable for fine tracking than it was for gross acquisition. The gross acquisition seemed like the response was a little delayed, but once you got it within the radical it was just about perfect for the fine tracking. And it responded well. Overall a HQR 2.

Runs 61 & 62; P4+40/R1; HQR 3: It felt better in pitch. Roll felt heavy or somewhat sluggish. HQR 3. overall. Not quite as nice as the last one. Roll felt unresponsive. Pitch seemed fine.

Runs 63 & 64; P4+40/R7; HQR 3: This time pitch seemed heavier than the roll. I didn't see any problem rolling it, but bringing the nose to bear pitch-wise seemed to be heavier. HQR 3.

Runs 65 & 66;P4+20/R1; HQR 2: I didn't really see any problems with it. I could almost call it a good baseline. I didn't see any problem with pitch or roll. Overall a HQR 2.

Runs 67 & 68; P4+20/R6; HQR 6: It was controllable. Adequate performance was available. Desirable was generally available. I had overshoots that may have dropped me out of the desirable regime. As I said it seemed like it was more sluggish in roll, tendency towards the roll PIO. Not real strong, this was almost the opposite as one of the other ones I had, in other words

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (continued)

it was difficult for fine the control, the gross control was not that great either. I particularly noticed the deficiencies in roll and particular more in fine tracking. HQR 6.

Runs 69 & 70; P4+80/R8; HQR 3: It is controllable. Adequate performance is always available. Desirable is generally available. I had two overshoots. HQR 3.

Runs 71 & 72; P4+40/R8; HQR 2: It was controllable. Adequate performance always available. Desirable performance always available. I particularly liked the roll procedures that I was able to do. In fact I felt the task was a little sluggish in pitch. The roll precision was fine especially for the fine tracking. HQR 2. It was slightly more sluggish in pitch than it was responsive in roll. I didn't really have any degrading performance to speak of.

Runs 73 & 74; P4+20/R8; HQR 1: All is controllable. Adequate is always available. Is it satisfactory? I had one overshoot and I would say that was more my fault than anything else. In general I was extremely pleased with how this was responsive both in pitch and roll. HQR 1.

Runs 75 & 76; P4/R6; HQR 5: It was controllable. Adequate performance was attainable. Desirable was not always available. Had some overshoots due to roll sluggishness. I could excite a mild roll PIO, by being very aggressive trying to set that up. HQR 5.

Runs 77 & 78; P4+20/R6; HQR 4: Controllable, adequate. Desirable attainable. Still some roll sluggishness. Pitch seemed to be fine. HQR 4.

Runs 79 & 80; P4+20/R7; HQR 3: Was adequate. Desired performance, yes. Had no overshoots that I could tell. HQR 3. The only thing I could think would be slightly heavy after required for roll. Could be the roll was slightly more sensitive. Pitch was fine.

Pilot Comments for a Formation Flying/Aerial Refueling Task
[The following pilot comments for the simulated Formation Flying/Air-Refueling task were taken from the experimentors notes]

Note: The following comments summarize the hand written notes taken as the pilot flew the task.
P4 - Rate Command (RC)
P6 - Attitude Command/Attitude Hold (RCAH)
P8 - Rate Command/Attitude Hold (ACAH)

Pilot 1:
P4/R2 configuration tracking a target 747.

Having problems tracking. Improving with practice. It feels like there is a delay in the visual which is causing the problem. There seems to be reasonable detail, at least to track the engines. I can judge fore and aft. Hard work. [Switch to P6 (ACAH).] More sensitive to inputs, but it takes less inputs. It is much easier than rate command. I can nail target with this system. I can almost take my hands off. Gain in pitch seems too sensitive. [Stick gain is reduced.] Reduced gain reduces bobbles. I can be fairly aggressive with this system.

Pilot 2:
P8/R1 configuration tracking a target 747.

[Pitch stick gain = -0.05, roll stick gain = 0.1.] HQR 7 or 8. Unacceptable for refueling because of pitch oscillation. [Switch to P6 (ACAH).] Better for this task. A lot better in pitch, roll is okay. Desired performance. HQR 4.

Pilot 3:
P4/R2 configuration tracking a target 747.

Tracking right engine from far away was easy. Move in closer. Very difficult. Visuals are sickening to my stomach. Start at pod 1 and put little circle on the fan. Give me 15 seconds to move to pod 4 and capture and track. Fighter pilots fly feet on the floor for tracking a tanker. [Switch to P6 (ACAH).] I hate flying rate behind a tanker. You get a ton of little bobbles. This

TABLE A-9. TRANSCRIBED PILOT COMMENTS
(edited for clarity) (concluded)

pitch command is a lot better. Power allows me to follow my 30° offset [below] from tanker with the attitude system. I can't do that with a rate system.

Pilot 5:
P4/R2 configuration tracking a target 747.

Pitch is a little sensitive. I get a PIO tendency when tracking. Most oscillations in pitch. HQR 5.5. [Switch to P6 (ACAH).] Much easier to come into precontact with this. Pitch is smooth. HQR 3. I can get desired most of the time. Unpleasant in lateral, mainly. [Switch to P6+40 (ACAH with 40°/s elevator rate limit).] Roll PIO sensitivity changed. Still PIO. Pitch no problem. HQR 3. Same comments as before.

Pilot 6:
P4/R1 configuration tracking a target 747.

Task is hard because the tanker is so indistinct. Rudder would help with small heading changes. Need an indicator of fore and aft like lights on the target aircraft. [Bring up a target KC-135 model with lights. This model gives streaks of color on the display.] Image is fuzzy. Still hard to see lights. Hard to tell if it's realistic for a fighter since I've only refueled with cargo planes. [Switch to P8 (RCAH). Pilot did not like this system.] I can determine fore and aft when I see the entire aircraft, but up close there is just not enough detail. [Switch to P6 (ACAH).] There seems to be a dead zone in the stick. Much more manageable than last configuration. I would like to use rudder instead of roll. A boomer would have no problem with this configuration. Much more controllable tracking right engine pod. No problems moving to the left. Throttle was real touchy.

APPENDIX B

INVESTIGATION OF THE ROLE OF VISUAL CUEING, RESPONSE-TYPE, AND TASK ON MISSION-ORIENTED FLYING QUALITIES

A. INTRODUCTION

1. Objectives of this Study

This Appendix summarizes the results of a Phase I Small Business Innovative Research (SBIR) study of the effect of interactions between the pilot's visual cue environment, the aircraft response-type, and the piloting task on handling qualities. The two major objectives of the study were to:

1. Create the structure, format, and methodology to incorporate these interactions into a mission-oriented specification; and

2. Generate the basic tables relating these elements, to the extent possible, based on available test data.

The first objective has been met in this Appendix. At the initiation of the study, it was hoped that flight test or ground simulation data could be located to use as guidance for completing the second objective. In a brief literature survey, however, it was not possible to locate any substantial evidence that the effects of cueing, response-type, and task have been evaluated in any formal research program for fixed-wing airplanes. There is a well-recognized relationship for the approach and landing task, where the absence of visual details in most ground-based simulators makes it difficult to achieve consistent, low touchdown sink rates. Even this relationship, however, has not been fully quantified.

The cueing/response-type/task tradeoffs have been the subjects of considerable work with helicopters, where operations in nap-of-the-earth, low-visibility conditions are not unusual. The helicopter research shows a clear relationship between these three elements.

In the absence of the desired supporting data, the approach taken in preparing this Appendix has been to complete the example structure for the handling qualities specification and then outline the required data to verify the structure. One or more ground simulation experiments, followed by a flight experiment, will be necessary to generate a foundation of supporting data.

2. Outline of this Appendix

Section B of this Appendix provides background information on the problems addressed in this study. Section C details the effects of visual cueing on piloted closed-loop control and the impact of these effects on handling qualities requirements. A proposed Visual Cue Rating scale is introduced in Section C as well. Section D expands the results of Section C to include the effects of response-type and task on handling qualities. Finally, Section E summarizes the conclusions from the study and Section F contains recommendations for future efforts.

B. BACKGROUND

1. Synopsis of the Problem

There is a growing dichotomy between the government approach to the specification of aircraft handling qualities and the requirements for mission effectiveness. The current military handling qualities standard, MIL-STD-1797A (Ref. B-1) is a comprehensive document that has, in some areas, evolved into a "cookbook" of requirements. Unfortunately, as extensive as 1797A is, there are still some aspects of the modern airplane mission that are not sufficiently covered by the cookbook. These aspects may be summarized as a lack of *mission orientation.* The standard does not provide the user the guidance necessary to translate the handling-qualities criteria into mission effectiveness criteria.

Mission orientation has been incorporated into the current U. S. Army military rotorcraft handling qualities specification (Ref. B-2). This specification is presently undergoing tri-service review for acceptance as a replacement to the current military specification on helicopter handling qualities. The specification is intended for use from the preliminary design stage through final evaluation and the effects of mission task, visual cueing environment, and response-type are embedded within its framework. The mission orientation of the specification allows the handling qualities of the helicopter to be optimized to the expected mission environment from the outset.

Mission orientation may be classified as a combination of the effects of the pilot's *visual environment* (cueing), the *response to controls* (response-type), and the specifics of the *mission task element* on handling qualities. None of these issues is addressed directly in MIL-STD-1797A. The closest the standard comes to any of these subjects is the mission task element, where requirements are generally divided by Flight Phase Category.

a. <u>Effects of Visual Cueing</u>

There is a recognized relationship between the pilot's visual environment and the achievable level of handling qualities. Beyond the basic requirements for the pilot to be able to recognize and avoid objects in the aircraft's flight path and to navigate, the visual environment determines the pilot's ability to perform precise closed-loop operations such as tracking a target, and flightpath control during approach and landing. The primary visual cues used by the fixed-wing pilot are attitude and flightpath (both horizontal and vertical). Secondary cues include speed and distance.

Visual cues necessary for closed-loop operations may be perceived either directly from the outside visual scene, or through a representation of the outside scene as displayed by a vision enhancing device (such as Night Vision Goggles (NVGs) or Forward Looking Infra-Red (Flir)), conventional symbology (such as a HUD or Multi-Function Display (MFD)), or a combination of these elements (a vision enhancing device with typical flight instrumentation symbology overlaid). In any case, the ability to perform closed-loop operations will depend on the quality of the visual information available to the pilot.

Certain mission task elements place specific demands on the pilot's ability to judge sink rate and trajectory. The most obvious of these tasks, and the one where some study has been performed, is the landing task. The most obvious example of the effect of visual cueing on handling qualities is the fact that, historically, pilot ratings obtained from ground-based simulations of the landing task are pessimistic when compared to ratings from equivalent in-flight testing.

The effect of the pilot's environment (in this case, both visual and motion) was evaluated in a ground-based simulation study conducted by NASA Langley Research Center (LaRC), reported in Ref. B-3. In this experiment, a simulation was performed on the LaRC Visual/Motion Simulator (VMS) that replicated, to the extent possible, the aircraft models, conditions, and task requirements of an in-flight simulation. The in-flight simulation used the USAF Total In-Flight Simulator (TIFS) to investigate handling qualities requirements for flared landings of transport airplanes, and the results of this study are published in Ref. B-4. In the Ref. B-3 ground-based simulation, the aircraft dynamics were based on the TIFS cases, but there were some differences resulting from the inherent time delays in the VMS simulator. In addition, there is an obvious difference in the motions experienced by the pilot between the TIFS and the VMS.

The results of the Ref. B-3 comparison study are interesting since it may be assumed that differences in pilot ratings or performance are due primarily to differences in the visual environment. The VMS used

a camera/terrain-board visual scene, projected to a CRT screen in the cockpit, that lacked the visual details available in the real world.

Pilot rating comparisons showed a more or less consistent degradation in average ratings for the VMS evaluations when compared to the TIFS. Examples of this are shown in Fig. B-1, where circle symbols are ratings from the VMS and squares are from the TIFS. There is no case in Fig. B-1 where the VMS ratings are significantly better than those of the TIFS; on the other hand, in several instances the VMS ratings are as much as two or more ratings worse than TIFS.

Pilot performance differences also reflected the impact of visual cueing. Figure B-2 illustrates the total percentages of landings within several landing performance parameters. There were fewer VMS landings within the defined desired regions for all of the parameters shown. The very small percentage of landings with desired values of sink rate (Fig. B-2a) reflects the lack of good depth perception on the visual scene, and the smaller number of landings within desired lateral and longitudinal positions (Figs. B-2b and B-2c) reflects a combination of lack of visual detail and field of view.

The data of Figs. B-1 and B-2 may be interpreted in two ways: 1) that the visual (and possibly motion) cues on the VMS were not adequate to accurately represent the real world; and 2) that the reduced visual cueing provided by the visual environment of the VMS resulted in an effective degradation in handling qualities not accounted for by aircraft-alone parameters. The second possible interpretation is, of course, the one of greatest interest here. It is support for the observation that *handling qualities are affected by the pilot's visual environment.*

Two specific examples from Fig. B-1 help illustrate the effects of visual cueing. Consider first Configuration 1 from the top plot in Fig. B-1. This case received Level 2 average ratings on the VMS but Level 1 ratings on TIFS. In an analysis of the TIFS data, published in Ref. B-5, the pitch attitude dynamics of this configuration (in terms of vehicle Bandwidth and phase delay) are very similar to Configuration B, which received Level 1 ratings from both experiments. The flightpath characteristics, however, are different, as Configuration 1 is on the border of Level 2 and Configuration B is solidly Level 1. The pilot ratings suggest, therefore, that the Level 2 ratings for Configuration B may be improved to Level 1 by improving either the response dynamics (make 1 look more like B) or the visual environment (make the VMS look more like the TIFS). If the visual environment is not changeable, one must change the aircraft dynamics.

As discussed above, the effect of the visual cueing environment is considered here in the context of its effect on the overall handling qualities. In other words, the emphasis is on the net result in terms of

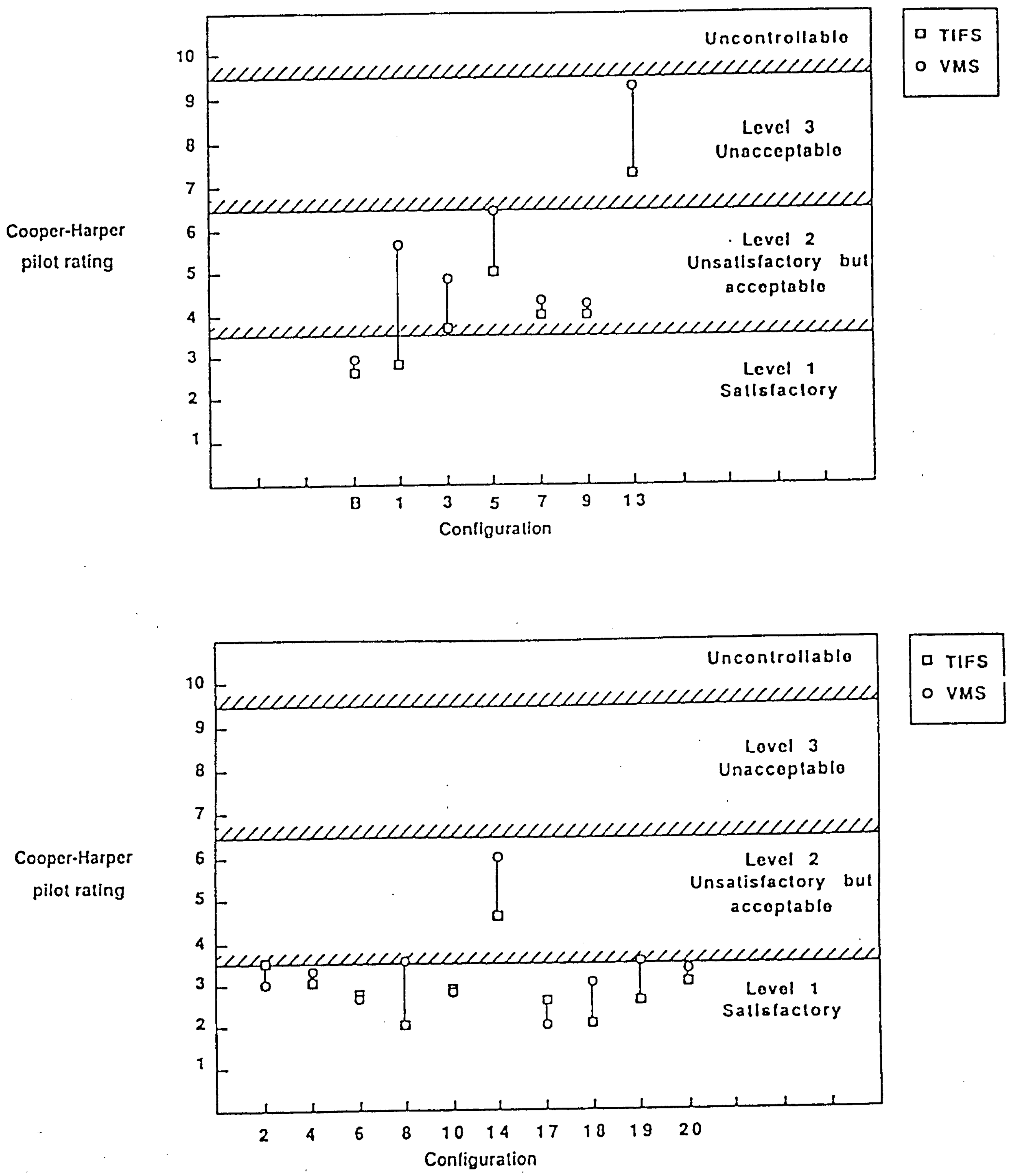
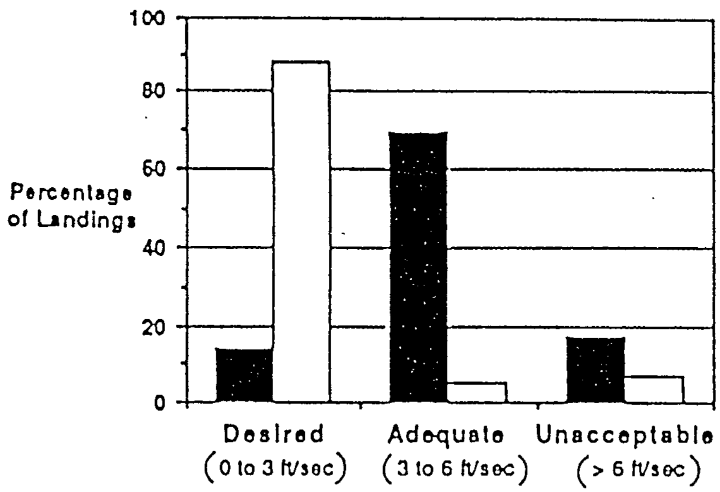
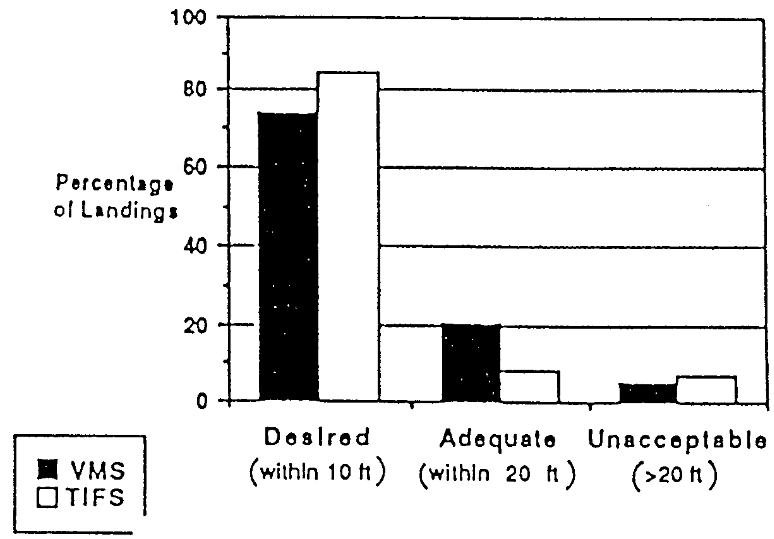


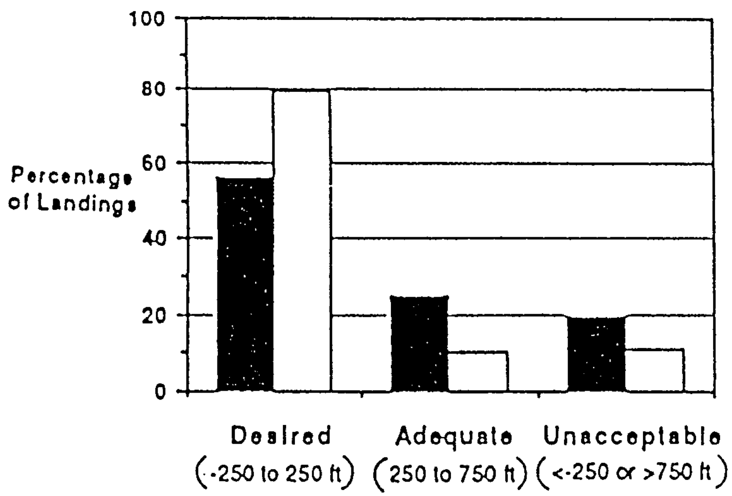
Figure B-1. Example of Degradation in Pilot Ratings for Ground-Based Simulation (VMS) Compared to In-Flight Simulation (TIFS) (from Ref. B-3)



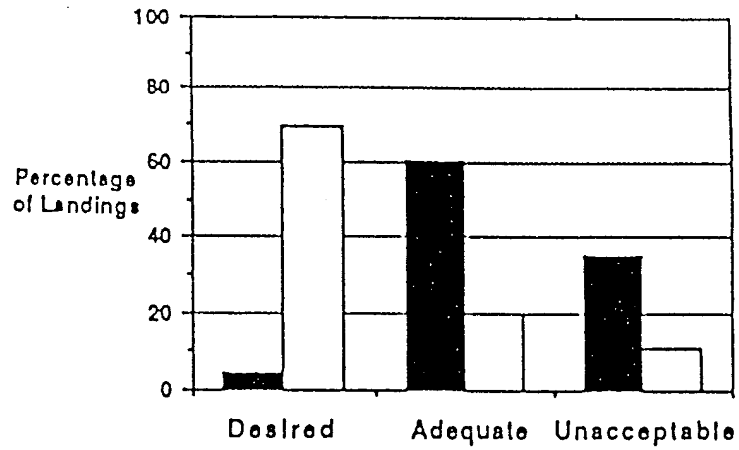
(a) Sink rate at touchdown.



(b) Lateral-runway position at touchdown.



(c) Longitudinal position at touchdown.



(d) Overall performance at touchdown.

Figure B-2. Landing- Performance Differences Between the TIFS and VMS (from Ref. B-3)

handling qualities due to the combination of the visual environment and the aircraft dynamics — not the specific content of the visual scene (or display) itself. Under this premise, the quality of visual displays that are used for tasks that are secondary to flying the aircraft will not be a direct factor. The quality of the visual information in these displays will determine the degree of divided attention that is required of the pilot and, thereby, impact handling qualities. The effect of divided attention operations on handling qualities, however, is not a subject for this study.

b. Effects of Response-Type

The technology to support fly-by-wire multi-mode aircraft is sufficiently mature that essentially all modern designs employ such systems. There is, however, little guidance in MIL-STD-1797A as to the proper response characteristics to minimize pilot workload throughout the flight envelope. Prior to fly-by-wire technology, tailoring of handling qualities was limited by the capabilities of the limited-authority stabilization and command system (SCAS). With the full-authority SCAS allowed by fly-by-wire, it is possible to achieve a wide variety of response shapes to control inputs. For example, the European Fighter Aircraft (EFA) has response dynamics that vary with airspeed, angle-of-attack, and stick position. The A320 fly-by-wire transport transitions from a rate to an attitude flight control system just prior to the landing flare.

Such aircraft have a wide range of possible control laws, allowing task-tailoring and definition of novel response-types to provide not only desirable *dynamic* response, but also optimal *type* of response to control inputs.

The study of the implications of response-type on piloted control was a significant portion of this effort. As a result, a separate section of this Appendix is devoted to the analysis of response-type and pilot dynamics. As a summary of the importance of response-type, Fig. B-3 shows pilot ratings from a study of task-tailored flight controls for the precision landing of a large hypersonic transport (Ref. B-6). This study was performed on the NASA LaRC Visual/Motion Simulator mentioned above. The abbreviations in Fig. B-3 are as follows: GCAH4 — pseudo-flightpath command/attitude hold; RCAH2 — rate command/attitude hold; ACAH1 — attitude command/attitude hold; and GCGH — flightpath command/flightpath hold. AT refers to autothrottle. As the ratings indicate, the worst response-type for precision landing was rate command/attitude hold and the best was flightpath command/flightpath hold. Most significantly, Pilot G, a highly experienced airline pilot with no previous experience as a test pilot, was unable to adjust comfortably to the rate command system during the simulation, even though

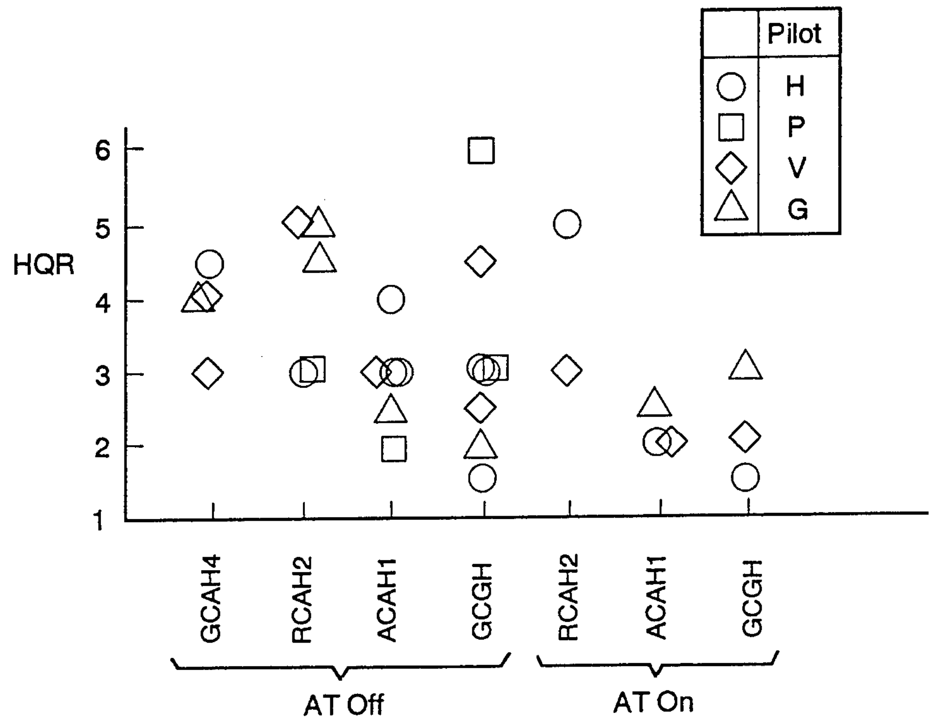


Figure B-3. Summary of HQRS for Primary Response-Types Evaluated in Precision Landing Simulation (Ref. B-6)

he was allowed more time with this system than with any other. This supports a preference for attitude or flightpath command over rate command for precision landing. (The results of the Ref. B-6 simulation are reviewed in greater detail later in this Appendix.)

c. <u>Effects of the Mission Task</u>

The Flight Phases that are included in MIL-STD-1797A are not fully representative of modern aircraft missions. This is true both in terms of the complexity of individual MTEs that are not well represented by the general Flight Phase and the level of performance required for each MTE. For example, in some cases the grouping of the Flight Phases into three Categories has resulted in inappropriate application of criteria. The landing task is a prime example. Landing (Flight Phase L) is a terminal Flight Phase, included in Category C in 1797A; for some aircraft, however, the stringent demands for precision landing make this task more relevant to the tracking phases in Category A. This deficiency was addressed for the USAF's STOL and Maneuvering Technology Demonstrator (S/MTD) program, where the landing was redefined to be a Category A task (Ref. B-7).

2. Visual Cue and Response-Type Requirements for Night Missions

a. Introduction

As a part of this Phase I effort, a brief literature review was conducted to gather "lessons learned" from night operations involving fixed-wing aircraft. This section presents the results of the literature review. Night operations were the most obvious topic to investigate in a preliminary search for information on the critical aspects of visual cueing in a degraded visual environment and observed associations between the visual environment, aircraft response-type, and pilot workload.

Night attack capability, with its increased element of surprise and promise of reduced casualties, has been an area of focus for both the U.S. Air Force and Marines for several years. The rapid development of sophisticated equipment for vision enhancement, precision weaponry, and advanced aircraft flight control systems, has made night attack an integral part of offensive strategy in present day conflicts.

The final intent of this particular research effort is to develop guidelines that may be used by a fixed-wing aircraft flight control system (FCS) designer to tailor the FCS to meet the handling qualities requirement for a particular task in a particular visual environment. This preliminary investigation into night attack requirements attempts to identify connections between task, visual environment, and FCS using an operational experience database. This section is, therefore, subdivided into subsections encompassing task (Mission Task Element, MTE), visual environment, and FCS (response-type).

The reference material that forms the background for this preliminary study, Refs. B-8 through B-20, consists primarily of anecdotal accounts of equipment tests and operational experience.

b. Mission Task Elements

The following MTEs have been identified in the reference material as being the most critical for night operations. They are required MTEs for any night mission, and they are the most demanding in terms of pilot workload.

- Low-level penetration (high speed - 450 kts, low altitude - below 200 ft)
- Night refueling
- Close formation flying
- Landing at a blacked-out airfield
- Air-to-air tracking
- Ground attack

All these MTEs are adaptations of general MTEs listed in the proposed categorization of tasks presented in Table B-1. It is safe to assume that most of the other tasks in Table B-1, with the possible exception of precision aerobatics, will also be appropriate for night operations.

c. Visual Environment

Few of the MTEs listed above may be performed successfully at night using the unaided eye alone. In general, a significant degree of illumination by moon and star light is necessary for safe VFR operations at night. For precision operations at night, however, vision enhancing devices such as night vision goggles (NVGs) and forward looking infra-red (Flir) are necessary. Radar may also be used for targeting and navigation.

Both NVGs and Flir are passive sensors that have the added attractiveness of stealth. Radar, being an active sensor, is used only intermittently for target and terrain recognition. This minimizes the risk of detection through aircraft emissions. It is reasonable to assume, therefore, that only NVGs and Flir are used to provide visual cues for piloted control of an aircraft.

- Night Vision Goggles (NVGs)

NVG technology is presently used most extensively in rotary-wing operations at low altitude. The binocular goggles provide an enhanced view of the environment by amplifying available reflected light.

Since the NVG depends on reflected light, on a clear moon-lit night it can provide sufficient visual cues for relatively aggressive and precise MTEs (see Table B-1). Descriptions of high-speed terrain following operations using NVGs are provided in the reference material (particularly Refs. B-8, B-9, and B-12). The flight evaluation programs mentioned in these references agree that the increased situational awareness afforded by the NVGs is essential (see Ref. B-11) for maneuvering around terrain at night.

The primary drawbacks of the NVGs are the limited field-of-view (approximately 30 deg) and the lack of depth cues. Both these factors affect the pilot's perception of lateral and longitudinal path and, thereby, forces the pilot to fly somewhat higher and slower than preferred. To compensate for this lack of depth perception, pilots use relative motion to judge the distance between objects in the visual field and the proximity of these objects to the aircraft (Ref. B-15).

In most of the operational accounts and flight trials reported in Refs. B-8 through B-20, the HUD is not integrated into the NVG system. The HUD brightness and cockpit lighting must, therefore, be specially adjusted to allow the pilot to use the information provided by the head-up and head-down instrumentation when flying with NVGs. The Ref. B-12 article

TABLE B-1. CATEGORIZATION OF MISSION-TASK-ELEMENTS

CATEGORIZATION OF MISSION-TASK-ELEMENTS			
Non-Precision Tasks		Precision Tasks	
Non-Aggressive (Category B)	Aggressive (Category D)	Non-Aggressive (Category C)	Aggressive (Category A)
Reconnaissance (RC)	Gross acquisition using loaded roll	Aerial recovery (AR)	Tracking maneuvering target (CO)
In-flight refueling - tanker (RT)	Missile defense with loaded roll	In-flight refueling as receiver (RR)	Ground attack (GA)
VMC and IMC loiter/cruise/ climb/descent (including emergency descent) (LO, CR, CL, D, ED, DE)	Anti-submarine search and maneuvering (AS)	Low altitude parachute extraction (LAPES)	Weapon delivery and launch (WD)
Normal takeoff (TO)	High speed max g turn	Catapult takeoff (CT)	Terrain following
Waveoff/go-around (WO)	"Herbst" turn	Approach (PA)	"Herbst" turn
Non-precision landing (L)	Split S, chandelle, hammerhead turn, loop, barrel roll, snap roll, etc.	Precision landing	Precision aerobatics, e.g., 8 point roll, etc.
	Scissors, high and low speed "yo-yo"	Close formation (FF)	
		Tactical final approach	

reports that the regular HUD/NVG combination was satisfactory and allowed head-up flight most of the time. In fact, the night-attack- adapted F-18D, reported in Ref. B-12, included a Flir image on the HUD as well. There were no reported difficulties in viewing the HUD/Flir image through the NVGs.

- Forward Looking Infra-Red (Flir)

The primary operational use of Flir is for target acquisition and tracking. Reference B-11 points out, however, that a relatively wider field-of-view Flir may also be used for navigation.

A high degree of resolution (and, therefore, narrower field-of-view) in the Flir is typically required for targeting.

Specific information about the visual cues (as related to aircraft control) afforded by the Flir is not available in the literature reviewed in this working paper. Reference B-11 mentions, however, the potential for visual miscuing that exists with the higher magnification, high resolution, Flir images. The magnified image provides the pilot with false path cues and, therefore, should not be used as visual feedback for navigation and control.

The primary advantage of Flir over NVGs is the ability to use Flir on nights with little or no illumination when NVGs are relatively ineffective. Most often, both NVGs and Flir are used together in a complementary way to provide the pilot with the best possible visual cues.

d. Response-Type

There is no evidence in the literature to support a link between handling qualities during night operations and aircraft response type (Rate Command and Attitude Command, for example). A primary reason for this is the relative uniformity of response-types presently in the military fleet (almost exclusively Rate Command or conventional). This fundamental link between available visual cues and response-type, demonstrated for helicopters, may not exists for fixed-wing aircraft in high-speed, low-level flight.

There is evidence that automatic modes are essential for relieving pilot workload, especially in single-pilot aircraft. Some of these automated modes have been tested on a specially fitted F-16 fighter (Ref. B-9). The specific modes evaluated were automated terrain following (TF), automated ground collision avoidance (GCAS), automated threat avoidance (TA), and a pilot activated unusual attitude recovery system (PARS).

It is inferred in the Ref. B-18 article and the Ref. B-9 Appendix that these automated modes are essential in a single-pilot night attack aircraft to relieve pilot workload. It is reported in Ref. B-8 that there is a significant time compression in certain flight phases during night attack for a single pilot; i.e., the workload becomes very high for short periods during critical phases of the mission. The primary means of relieving this time compression and reducing the workload during these flight phases is to automate as many functions as possible.

There is no information in the reference material on the visual delays associated with the NVG and Flir systems. It is possible that improvements in the handling qualities of the aircraft may be used to offset, to an extent, such deficiencies in the visual systems.

e. Conclusions of the Literature Review

This preliminary literature review provided a general idea on the operational aspects of visual cueing, task, and response-type in a degraded visual environment (night). Presently, the anticipated night missions are effectively the same as those commonly performed in a more favorable (day-time) visual environment.

The primary visual aids for night-time flying are NVGs and Flir systems with varying resolution. The pilot workload associated with performing missions using these systems is high. Automated modes, such as automatic terrain following, greatly improve the task effectiveness during night operations by relieving pilot workload. This is especially true for single-pilot aircraft.

C. EFFECTS OF VISUAL CUEING ON CLOSED-LOOP CONTROL

1. Concept Development (Using Piloted Control of Helicopters)

The concept of an interrelationship between visual cueing and handling qualities was originally developed for inclusion in the U. S. Army's helicopter handling qualities specification (Ref. B-2). These interrelationships, when incorporated into the mission oriented framework of the specification, allow the designer to properly account for the expected mission environment of the helicopter when designing the flight control system. The motivation for the development of these concepts stemmed from practical considerations (derived from practical experience) arising from the wide and varied nature of the modern helicopter's mission environment including low-level operations at night using visual aids. The visual environment, as defined in the specification, refers to the visual information that is available to the pilot from the outside visual scene, a visual display, or a combination.

The helicopter handling qualities specification (Ref. B-2) incorporates the effect of the visual environment on handling qualities in three different ways. First, the appropriate response of the helicopter to control inputs (response-type) is specified based on the visual environment. Second, specific response requirements (such as Bandwidth) are specified as a function of the visual environment, and third, demonstration maneuvers that are commensurate with the visual environment are specified. The substantiating data and theoretical bases for these concepts are discussed in depth in the Background Information and User's Guide for the helicopter handling qualities specification (Ref. B-21). As a precursor to the extension of these concepts from helicopters to fixed-wing aircraft, it is useful to revisit the related discussion on this subject that is provided in Ref. B-21 in order to gain a better understanding of these concepts.

a. Effect of Response-Type

The fundamental basis underlying the definition of required response-types based on visual environment is the need for increased stabilization as the available visual cues decrease. This concept is based on the somewhat intuitive notion of a tradeoff (in terms of handling qualities) between the visual cueing environment and the aircraft dynamics. For helicopters, this observation has been corroborated by a substantial amount of experimental evidence. In Ref. B-21, the theoretical basis of this observation is investigated using a closed-loop pilot-vehicle analysis of a longitudinal position keeping task (a hover task). The analysis specifically examines the effect of the pitch attitude dynamics on the piloted control of longitudinal position. A block diagram representation of this pilot-vehicle system is presented in Fig. B-4.

The illustrative example in Fig. B-4 examines the effect of four different pitch response-types on piloted control of longitudinal position. The augmented rotorcraft dynamics in Fig. B-4 represent the four different pitch response-types. The pilot is represented by a pure gain and first-order lead equalization. The pilot attempts to maintain position by minimizing longitudinal position error.

The root loci for the piloted closure of a position loop using four different pitch response-types are shown in Fig. B-4. The locus of the closed-loop position mode is identified. This mode is dominant and determines the frequency and damping of the closed-loop longitudinal position response of the pilot-vehicle system. The amount of pilot lead compensation ($1/T_{Lx}$) that is applied is kept constant over the four different response-types that are compared. Pilot lead compensation is generated from position rate information that is directly perceived (or mentally computed) using available visual cues. The root loci indicate that, in the case of the Rate and Rate Command/Attitude Hold (RCAH) response-type, the pilot will have to close an inner pitch attitude loop for the closed-loop position response to be stable. Directly closing a position loop with these two systems will result in an unstable position response for any value of pilot lead. Conversely, with the Attitude Command/Attitude Hold (ACAH) and Linear Acceleration Command (LAC) systems, the pilot may maintain a stable hover position without closing an inner pitch attitude loop. Also, with these systems, the damping of the closed-loop position mode may be improved by increasing the amount of pilot lead equalization.

The analysis in Fig. B-4 indicates that the pilot would have to provide the necessary stabilization (in the form of an attitude loop closure and additional position lead) in order to maintain a stable hover with the Rate and RCAH response-types. Under any circumstances, this added stabilization will incur a penalty in terms of increased pilot workload. Also, in high workload situations and degraded visual conditions

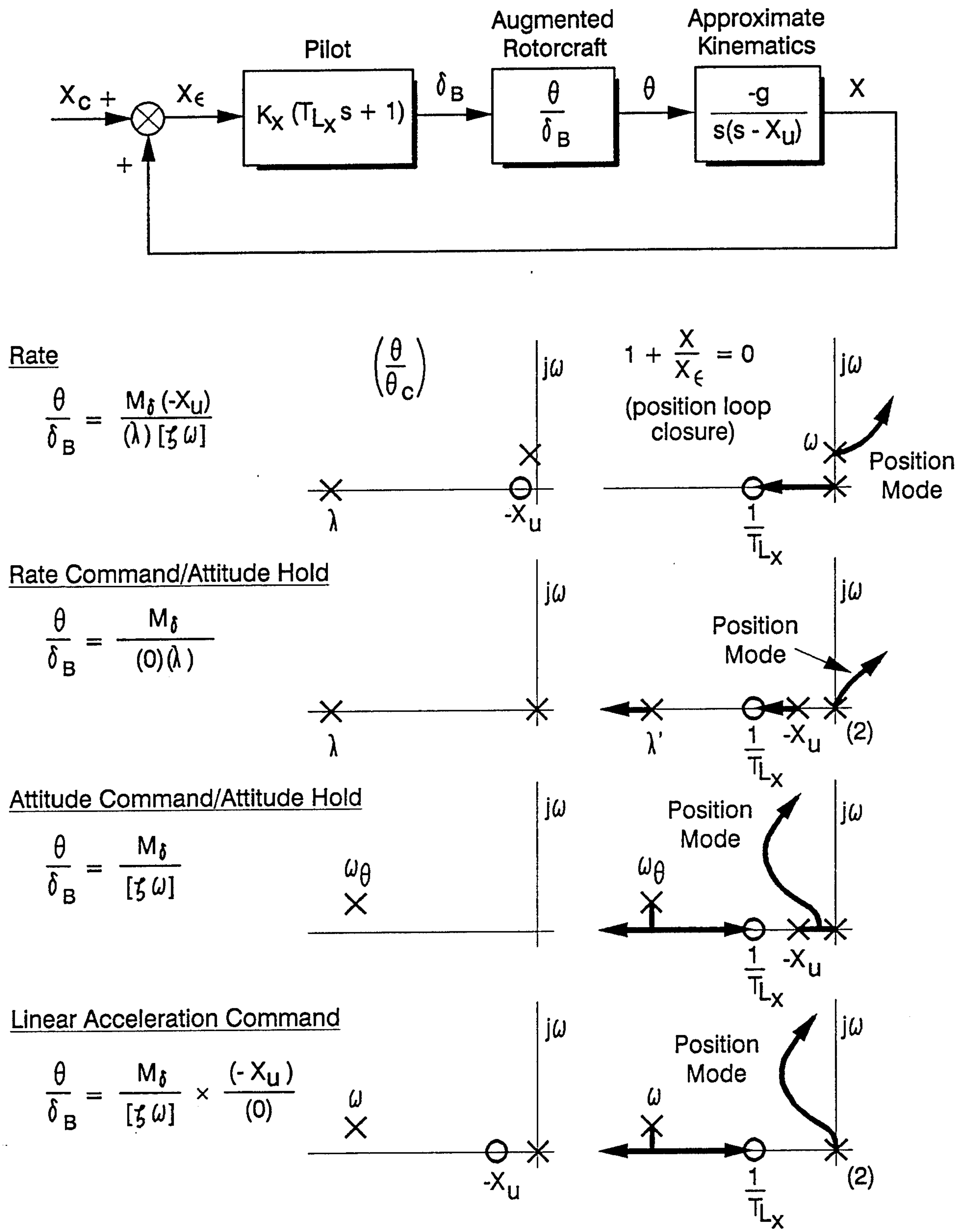


Figure B-4. Effect of Augmentation Types on Pilot Position Loop Closure (from Ref. B-21)

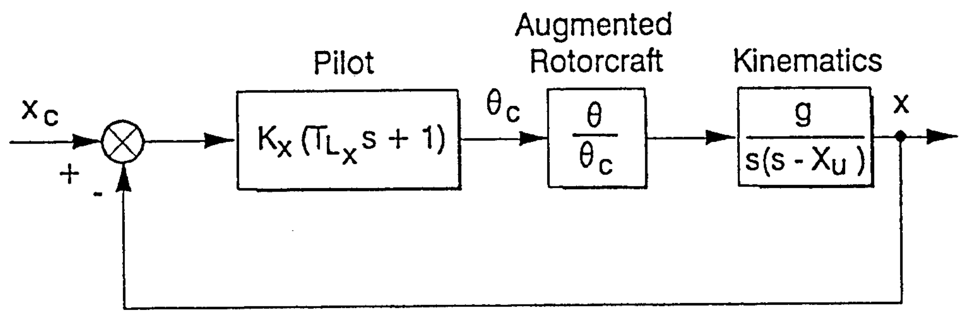
the pilot's ability to closely regulate attitude will most likely be impaired. In such operational environments, therefore, it may be assumed that the ACAH and LAC response-types will be preferred since close regulation of pitch attitude is not mandatory with these systems.

The reasoning in the previous paragraphs has been verified experimentally through flight tests. It illustrates the concept of tailoring the response-type based on task to reduce pilot workload. It also infers the suitability of some response-types over others in performing these tasks in degraded visual conditions.

b. Effect of Bandwidth

The background data for the helicopter specification (in Ref. B-21) also indicated the need for more stringent response requirements for operations in high-workload situations including operations in degraded visual environments. The theoretical basis for this may also be illustrated using the example discussed above. Specifically, it can be shown that with the most suitable response-type (for example, ACAH) an increased response bandwidth may improve the pilot's ability to maintain position with reduced pilot workload. Such a response-type/response bandwidth combination will, in all probability, facilitate better handling qualities during degraded visual environment operations.

Figure B-5 repeats the block diagram of Fig. B-4 and illustrates the effect of the pitch attitude bandwidth of the ACAH system on the closed-loop position mode. The Bandwidth parameter, defined in Fig. B-6, is an indicator of the frequency range available to the pilot for achieving stable closed-loop control. Figure B-5 illustrates the benefits of increased pitch attitude bandwidth on the position loop closure with the pilot providing a fixed lead equalization at 0.25 rad/sec. As the pitch attitude bandwidth (ω_{BW_θ}) is increased, the closed-loop position mode locus becomes increasingly more stable with no additional compensation required of the pilot. As a result, with the higher bandwidth systems, the pilot will be able to adjust his gain over a wider range of gains without jeopardizing closed-loop stability. With the lower bandwidth systems (ω_{BW_θ} = 1.0 rad/sec, for example), the pilot would have to provide some additional compensation in order to ensure stable operation. These factors, when combined, indicate that the pilot workload associated with the position loop closure will be decreased as the pitch attitude bandwidth is increased. It may be assumed, therefore, that in a degraded visual environment where the workload is high, increased pitch attitude bandwidth will be desirable in order to minimize the amount of pilot compensation that is required to maintain position with resulting improvements in handling qualities.



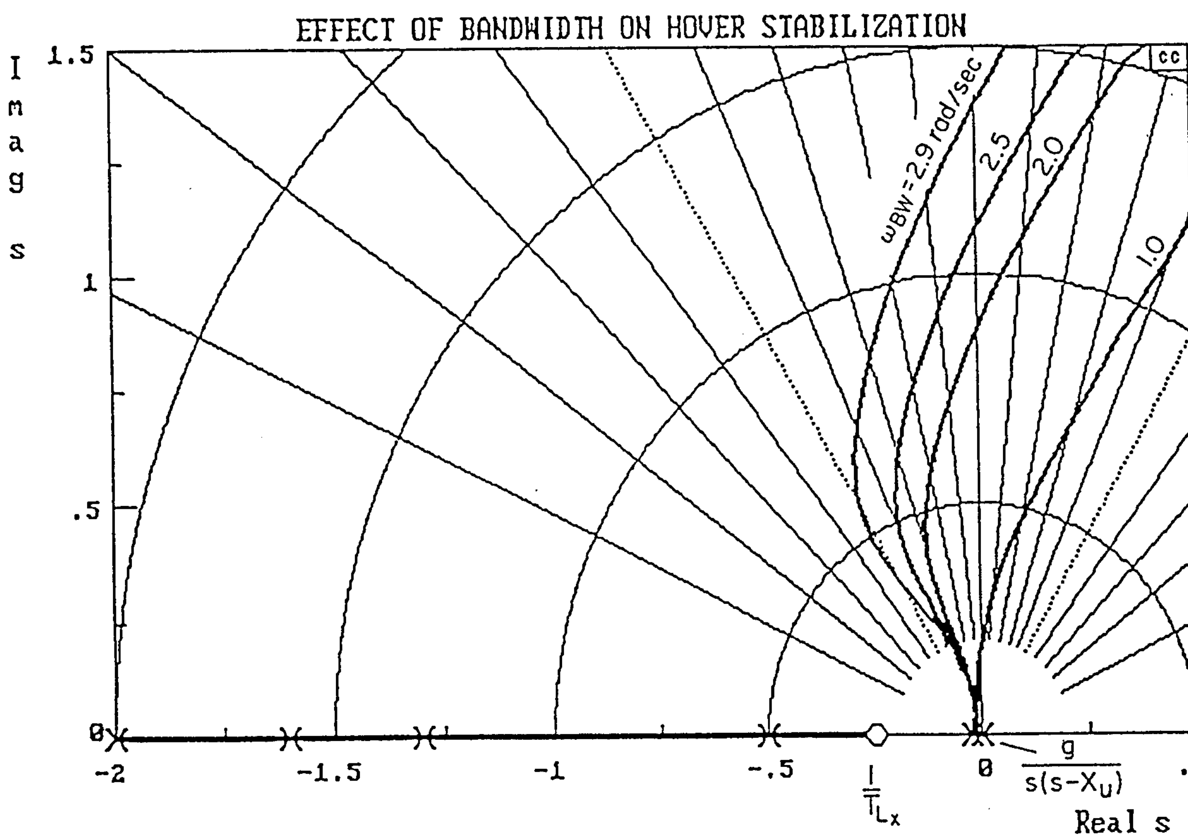


Figure B-5. Loci of Pilot-Vehicle Position Mode for Hover Stabilization of a Helicopter as a Function of Pitch Attitude Bandwidth (from Ref. B-21)

Phase Delay:

$$\tau_p = \frac{\Delta\Phi 2\omega_{180}}{57.3(2\omega_{180})}$$

Note: if phase is nonlinear between ω_{180} and $2\omega_{180}$, τ_p shall be determined from a linear least squares fit to phase curve between ω_{180} and $2\omega_{180}$

> *CAUTION:*
> *For ACAH, if $\omega_{BW_{gain}} < \omega_{BW_{phase}}$, or if $\omega_{BW_{gain}}$ is indeterminate, the rotorcraft may be PIO prone for super-precision tasks or aggressive pilot technique.*

Rate Response-Types:

ω_{BW} is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$

Attitude Command/Attitude Hold Response-Types (ACAH):

$\omega_{BW} \equiv \omega_{BW_{phase}}$

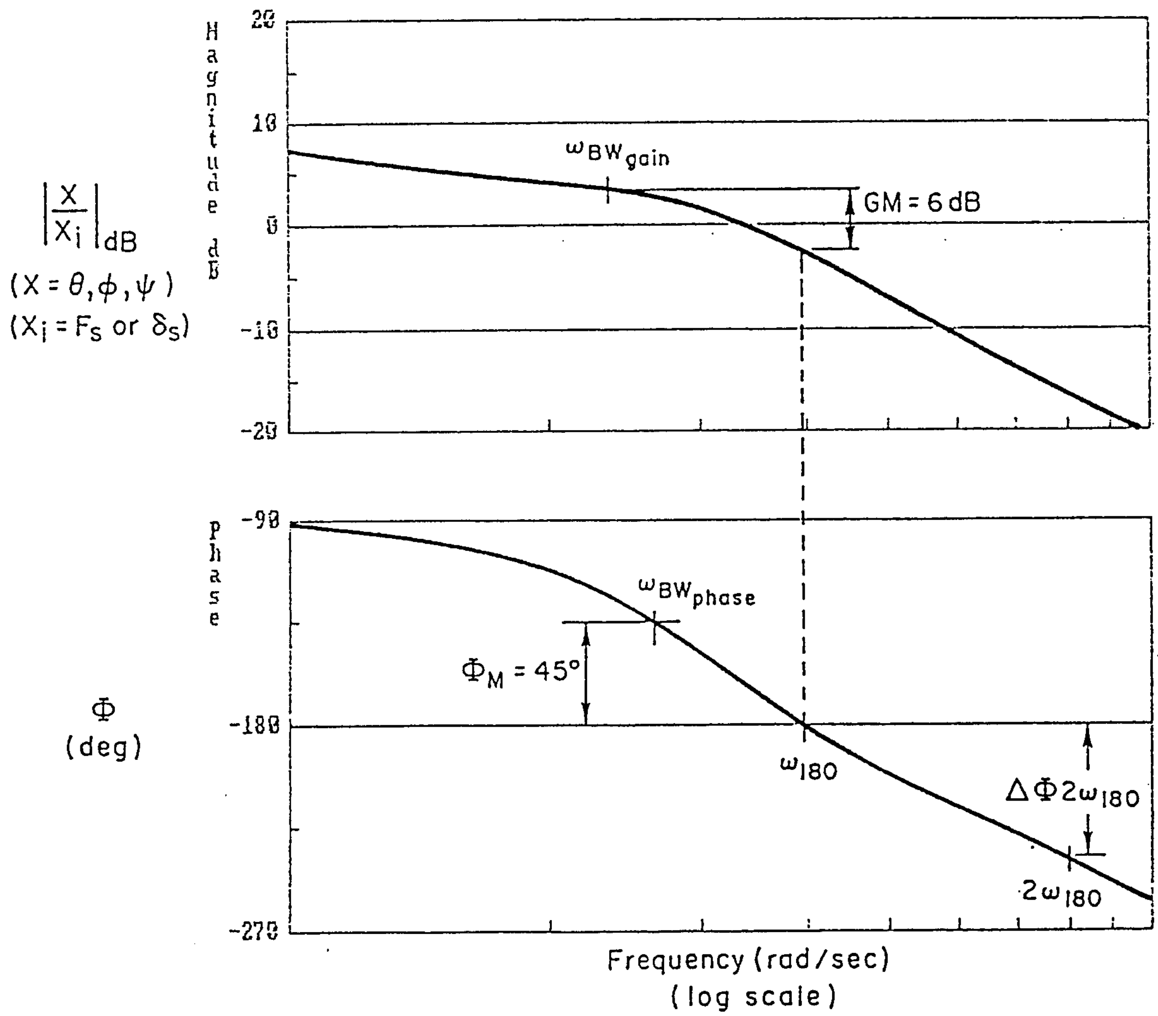


Figure B-6. Definitions of Bandwidth and Phase Delay (from Ref. B-21)

c. Extension to Fixed-Wing Aircraft

These concepts, developed for helicopters, may be extended with some modification to fixed-wing aircraft. Specifically, modifications will be required to account for the differences in the mission environments of the helicopter and the fixed-wing aircraft. In general, the mission environment of a conventional airplane does not demand the degree of precise closed-loop attitude control required in a helicopter mission environment. The greater flight speeds involved in fixed-wing aircraft operations do not normally allow compensatory closed-loop operation. Most often, piloted control of a fixed-wing aircraft may be expected to involve precognitive- or pursuit-type pilot operation.

Situations in fixed-wing operations that require tight closed-loop control include precision approach and landing and terrain following. In these and other fixed-wing operational tasks the primary outer control loop is horizontal and vertical flightpath (as opposed to helicopters, where it is position). Attitude regulation serves as a fundamental inner stabilizing loop for path control in most situations. Clear attitude cues are also essential for tracking and pointing tasks where precise attitude control is required.

The requirement for good attitude cues is fundamental to flight. The discussion in this Appendix assumes that clear attitude cues are always available. This is true in all aircraft. In the absence of a discernable horizon, attitude cues are always provided to a pilot by an Attitude Director Indicator (ADI) and, in some cases, a HUD.

The closed-loop pilot-vehicle analysis technique used to illustrate the effect of response-type and bandwidth on pilot workload and handling qualities may also be applied to fixed-wing aircraft to assess the impact of the visual environment on handling qualities. Prior to such an analysis, however, it is necessary to gain an understanding of the manner by which the pilot derives path information from the available visual cues.

2. Visual Cues Necessary for Path Control

There are several visual stimuli that a fixed-wing pilot may use to judge the flightpath and speed of the aircraft. In addition to these two important states, other information such as closure rate and altitude may also be derived from visual stimuli. A list of visual stimuli and corresponding pilot cues is presented in Table B-2.

TABLE B-2. LIST OF VISUAL CUES

Visual Input	Pilot Cue
Streamer field	Instantaneous velocity vector, curvature preview (horizontal and vertical "aim-point")
Apparent size and range of objects	True range (using visual perspective and vanishing points)
Perspective distortions (perceived changes in geometrical shape)	Position relative to a object (usable for clearly defined outlines – buildings, runways, etc.)
Perceived rate of change of the dimensions of an object	Velocity and acceleration relative to an object
Perceived gradients in ground texture	Distance
Perceived rate of change in ground texture	Closure rate, vertical velocity, and relative angular velocity

The cues listed in Table B-2 are, in most cases, derived from the outside visual scene. In the absence of clear outside visual information, these cues may be derived from images of the outside visual scene from specialized sensors or instrumentation that can directly provide the cue (such as a flightpath vector). In some cases, cues such as the flightpath vector are superimposed on the outside visual scene or sensor image of the outside visual scene and provide the pilot with clear cues that may not be available, or are difficult to discern, from the outside visual scene alone.

In good visual conditions, the pilot may use any or all of the stimuli in Table B-2 to obtain an accurate assessment of the flightpath. In degraded visual conditions, such as would be experienced in fog or when using current vision enhancing devices at night, the quality of most of these cues will be significantly degraded and sometimes lost altogether.

In terms of motion perspective, the streamer field represents the clearest flightpath cue (Ref. B-22). As indicated in Table B-2, the streamer field provides a measure of the instantaneous velocity vector from which other potential path control feedback quantities such as horizontal path curvature may be derived. Detailed discussion of the streamer fields and their use in assessing flightpath is presented in the next section of this Appendix.

In a good visual environment such as clear daytime conditions, streamer information can be used to directly perceive path curvature and, thereby, provide lead information for path control. Perception of path curvature is contingent on good visibility (i.e., an adequate "look ahead" distance). The accuracy of

the path curvature information increases and the perceptual workload incurred in deriving this information from the visual scene decreases the further the pilot is able to see. In a degraded visual environment, where the visual range is decreased, the pilot's ability to judge curvature will be impaired. The perceptual workload incurred in judging path curvature using the limited look-ahead distance available will also increase.

The ability to discern path curvature information from a visual streamer field and the effect of visibility on this capability has been examined in automotive studies. Typical visual scenes, representing varying roadway visibility from a man-in-the-loop simulation study of driver visibility requirements for roadway delineation (Ref. B-23), are shown in Fig. B-7. These scenes from a driver's perspective illustrate the path curvature information that can be perceived from the roadway delineations. It also illustrates the degradation in this information as the visibility and, therefore, the look-ahead distance is reduced.

In an aircraft following a specific horizontal path at low altitude, streamer information from ground-based objects and texture will facilitate path curvature perception in a manner that is analogous to the roadway delineations shown in Fig. B-7. With current vision enhancing devices such as NVGs, or typical flight simulator visual displays, the content of the visual scene and, therefore, the density of the streamer field will be greatly reduced. This decreases the pilot's ability to judge curvature and increases the pilot's perceptual workload.

In the longitudinal axis, the streamer field provides the pilot with an estimate of the instantaneous glidepath (instantaneous aim-point). A typical block diagram for the piloted control of glidepath is presented in Fig. B-8a. If clear attitude cues are available, the pilot may also close an inner pitch attitude loop with a resulting increase in workload. As will be shown later, stable control of glidepath may be achieved without tight regulation of pitch attitude.

In the directional axis, the pilot may derive both path and curvature information from the streamer field. A typical block diagram for the piloted control of lateral flightpath (λ) is presented in Fig. B-8b. The time factor (T_G) is a look-ahead time (corresponding to a look-ahead distance D_μ) that is necessary for estimating curvature (essentially the second derivative of lateral position). The position,). The curvature feedback provides essential lead information for flightpath control. It will be shown later that in good visual conditions, when the look-ahead distance (and look-ahead time) is considerable, horizontal flightpath may be controlled without an inner roll attitude regulation loop. In degraded visual conditions, when the look-ahead time is small, an inner roll attitude regulation loop will be required to ensure stability.

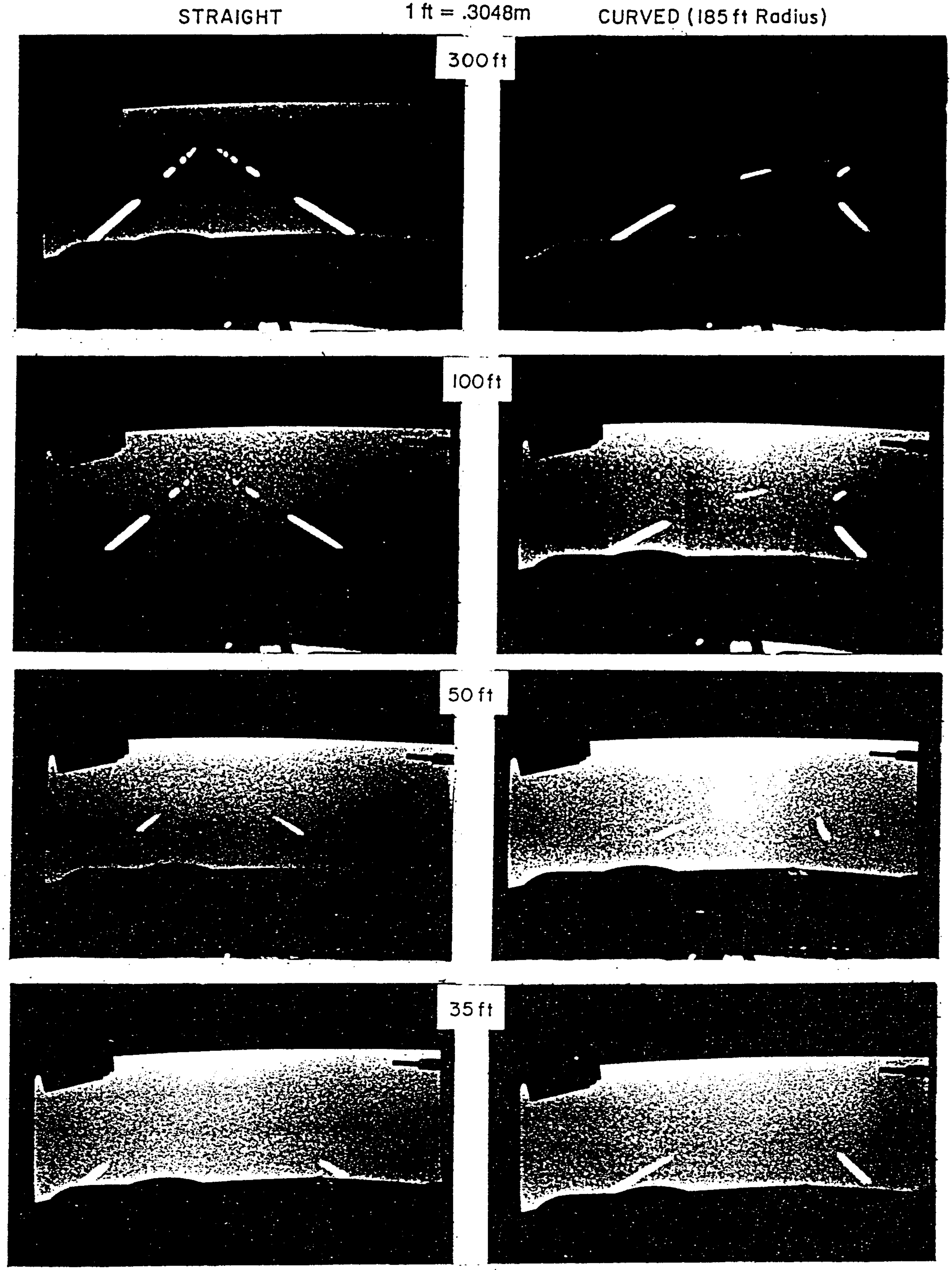
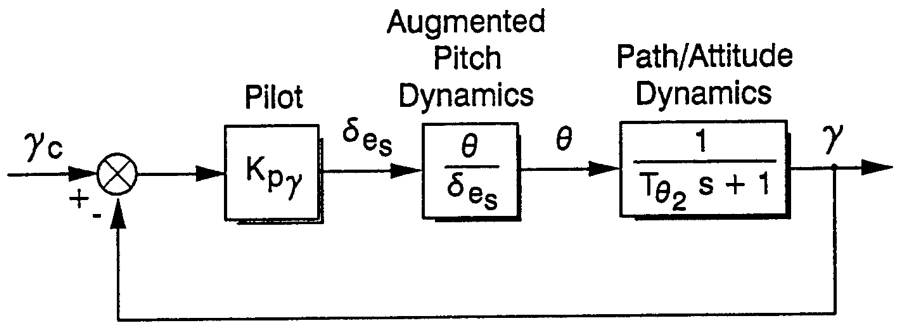
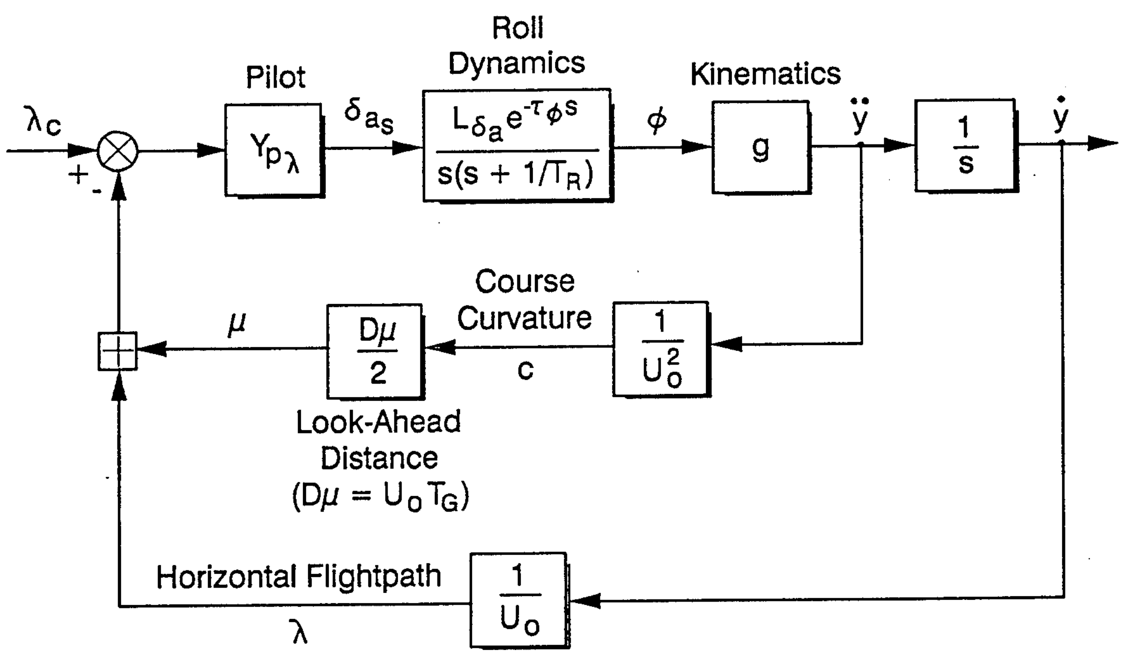


Figure B-7. Federal Standard Delineation Striping Under Various Levels of Reduced Visibility (from Ref. B-23)



a) Vertical Flightpath Control



b) Horizontal Flightpath Control

Figure B-8. Pilot-Vehicle Block Diagrams for Flightpath Control

A research study on the effect of the visual environment on the prediction of curvature by a pilot is reported in Ref. B-24. The experiment investigated the effects of the velocity-to-height ratio, the viewing distance, and the terrain type on the estimation of instantaneous horizontal flightpath. The effect of obscuring parts of the visual field was also investigated. The experiment was conducted using a workstation-based graphical user interface. The results of this study indicated that a significant time penalty (pilot time delay) is incurred when the far-field cues are obscured. Obscuring the far-field cues essentially reduces the look-ahead distance (and time) and is representative of the visual scenes provided by current-day night vision enhancing devices such as Night Vision Goggles (NVGs) and Forward Looking Infra-Red (Flir). The added human time delay incurred when the far-field cues are obscured is caused by the increased processing time (increased perceptual workload) that is required for the pilot to extrapolate the future flightpath from the available near-field cues.

The Ref. B-24 study also found that the near-field cues provide an essential speed cue and that the prediction of curvature improved with increasing flight speed. This is primarily due to the more continuous nature of the streamer field (streamer "flow") at higher speeds. Increasing flight speed reduces the time interval between elements in the streamer field making it appear more continuous (essentially increasing the sampling frequency of the visual information). This phenomenon has also been observed in automobile research where drivers sometimes attempt to derive better curvature information by increasing their speed even though visual conditions are degraded and look-ahead distances are small (Ref. B-23).

3. Motion Perspective Using "Streamer" Cues in the Visual Field

The good description of the pilot visual cues that may be perceived from the streamer field is presented in Ref. B-22. The discussion in this section is derived from Ref. B-22.

The apparent motion of single points that are fixed in inertial space gives rise to streamers of point images, and the apparent motion of inertially-fixed point sets gives rise to the phenomenon of motion perspective, created by the streamers of the point set.

If individual fix points in inertial space are continually observed in uni-directional monocular viewing with the line-of-sight (LOS) fixed (or continually moving) in a moving frame, the locus of each fix point is perceived as a continuous curve, called a "streamer." When viewing a point set on a ground plane fixed in inertial space, a set of correlated streamers is generated that constitutes an expansion pattern of the region defined by the point set. If the observers motion is rectilinear at any instant, this expansion pattern is seen to emanate from an individual motionless "focus of expansion" located at the intersection

of the instantaneous velocity vector of the moving frame with the ground plane of the inertial space. This expansion pattern of the streamer set is perceived as the "motion perspective."

Motion perspective offers the observer the means to discern the point toward which a vehicle is moving (aiming point). An observer traveling over (and parallel to) a ground plane in a straight line will perceive textural streamer cues as illustrated in Fig. B-9a. If the observer is following a curved path, the focus of expansion no longer exists, and the streamer velocities will have an added component due to the observer's turn rate and will appear as illustrated in Fig. B-9b.

Figure B-10 presents an analysis showing how the interpretation of motion perspective geometry will enable an observer to anticipate changes in the future course of the motion in horizontal flightpath. When present and recognized, these essential visual elements from motion perspective will enable an observant controller to provide lead compensation of the controlled element without the customary intensive mental workload that accompanies visual anticipation and lead equalization of low-frequency motions.

In a degraded visual environment where the density of the textural field in low, the focus of expansion (aim point) of the streamer field will not be as readily apparent. In such situations, the aim point must be extrapolated by the observer using the limited streamer field available in order to generate the lead equalization necessary for precise control. As may be expected, this will incur a cost in terms of added pilot mental workload.

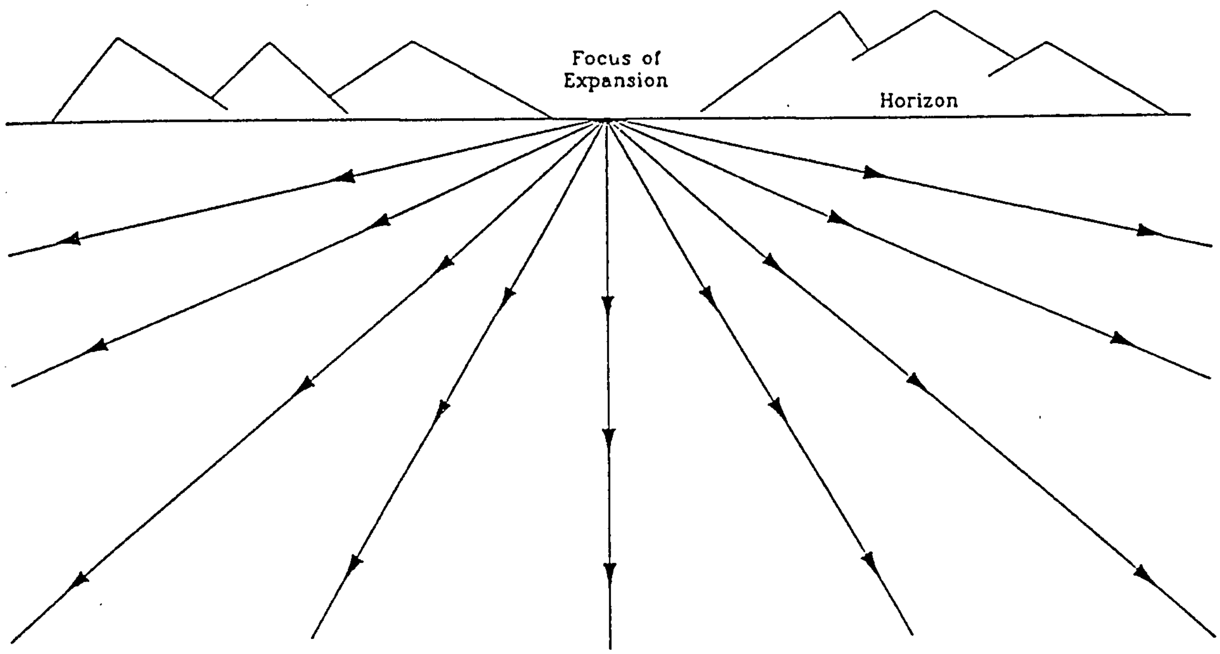
4. Effects of Visual Cueing on Handling Qualities Requirements

The closed-loop pilot-vehicle analysis used to describe and understand the interrelationship between visual cueing and handling qualities in helicopters can be used to make a preliminary assessment of the handling qualities implications of the visual environment on longitudinal and lateral flightpath control in fixed-wing aircraft.

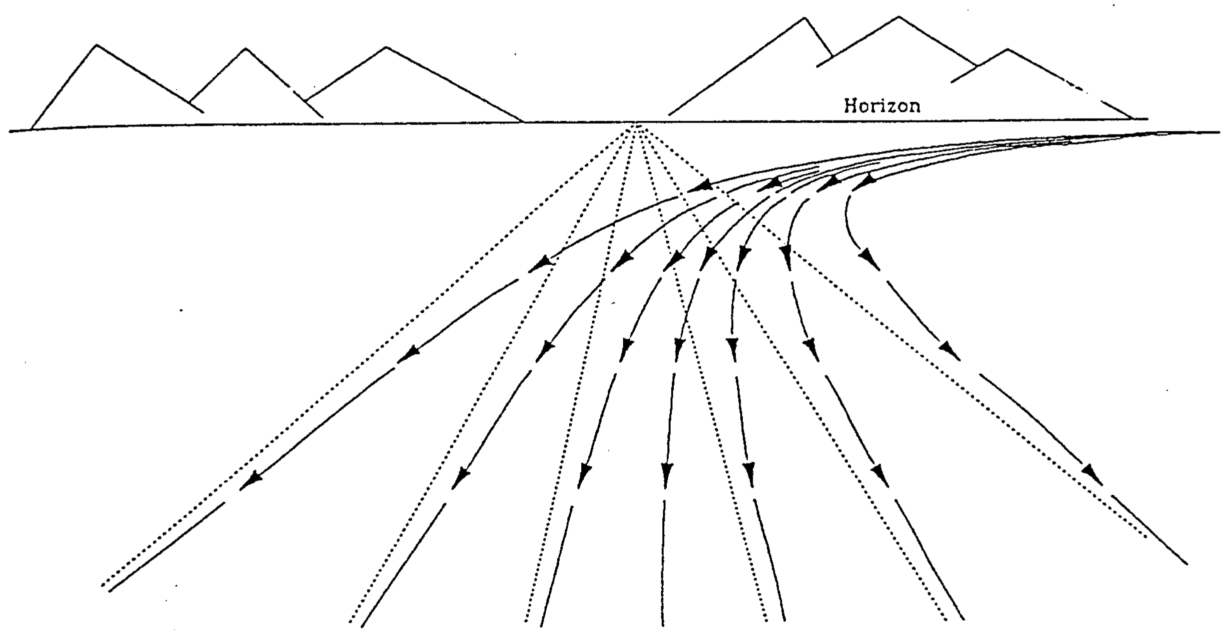
a. Longitudinal Flightpath Control

The effect of pitch response-type on piloted longitudinal flightpath control is examined in Fig. B-11. The analysis in Fig. B-11 adheres to the same pilot-vehicle principles outlined previously in the assessment of piloted control of position in a helicopter (Fig. B-4).

The block diagram in Fig. B-11 describes the assumed pilot-vehicle system. The system has the same structure as that outlined in Fig. B-8a. Visual information on glideslope (γ), obtained from outside visual cues and/or a flightpath vector on the HUD, is used by the pilot to compute a glideslope error. The

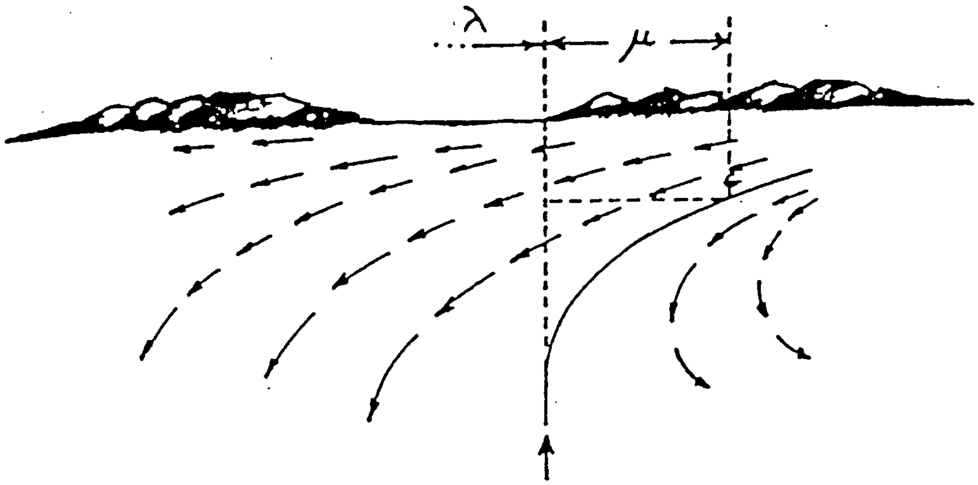


a) Straight Ahead Flight Over a Horizontal Plane



b) Curved Path Flight Over a Horizontal Plane

Figure B-9. Motion Perspective from Streamer Fields (from Ref. B-22)



Instantaneous direction of velocity corresponds to azimuth of streamer vector that becomes asymptotically vertical to the lower limit (nadir) of the visual field

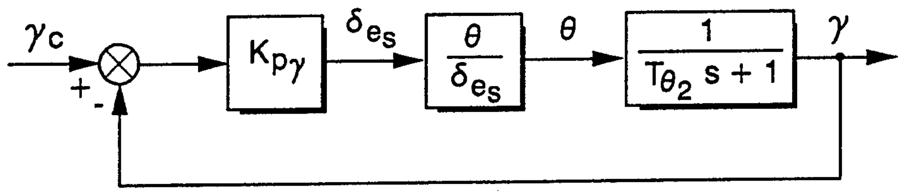
A point, G, on the future ground track at distance D and time T_G ahead of the present position and course will subtend an azimuth angle of μ.

Whence

$$\mu = \frac{\ddot{y}T_G}{2V_G}\left(\frac{D_\mu}{D_\mu}\right) = \frac{\ddot{y}D_\mu}{2V_G^2} = \frac{T_G^2}{2}\ddot{\varepsilon}$$

where
- ε lateral displacement angle with respect to runway centerline, y/D_ε
- y lateral displacement with respect to the centerline
- D_μ ground distance-to-go to the point of regard in the visual field for defining μ
- V_G ground velocity of observer
- T_G Time-to-go the distance D_μ, D_μ/V_G

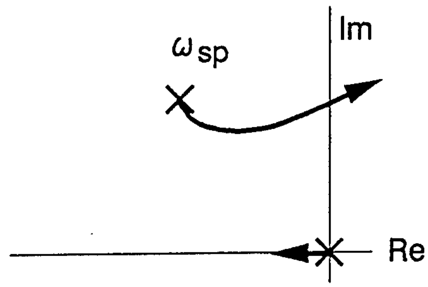
Figure B-10. Curvilinear Motion Perspective Streamer Vectors in the Visual Field ahead During a Horizontal Turn (from Ref. B-22)



Path Loop Closure

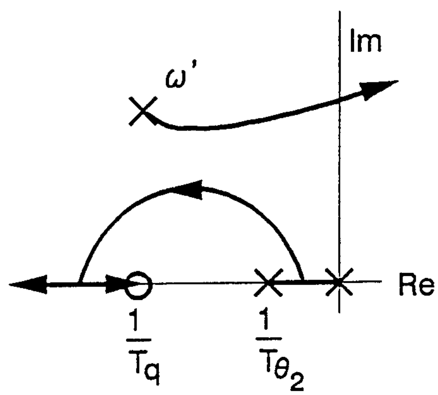
Rate

$$\frac{\theta}{\delta_{es}} = \frac{M_\delta (1/T_{\theta_2})}{s[\zeta_{sp}, \omega_{sp}]}$$



RCAH

$$\frac{\theta}{\delta_{es}} = \frac{M'_\delta (1/T_q)}{s[\zeta', \omega']}$$



ACAH

$$\frac{\theta}{\delta_{es}} = \frac{M'_\delta}{[\zeta', \omega']}$$

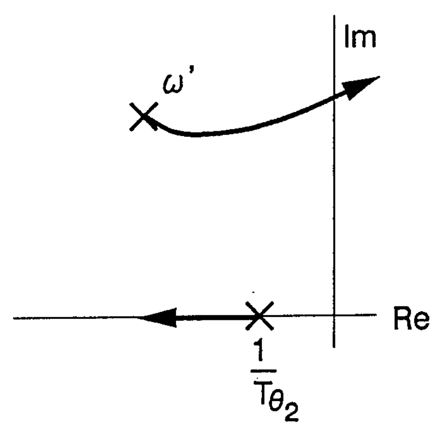


Figure B-11. Effect of Pitch Response-Type on Longitudinal Flightpath Control

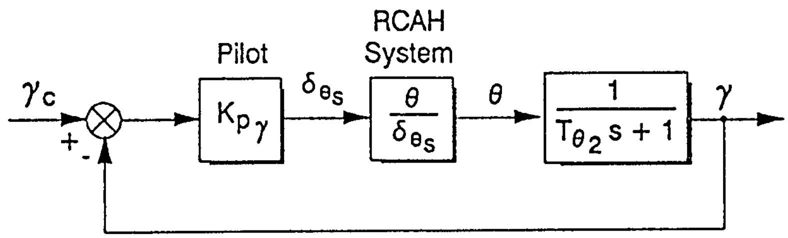
pilot then adjusts pitch attitude to minimize the glideslope error. In Fig. B-11, the pitch dynamics of the augmented aircraft are represented by three different response-types — conventional (represented by the short-period approximation), RCAH, and ACAH. For this example, it is assumed that the pilot uses outside visual cues only (no direct flightpath vector information) and, therefore, does not have clear glideslope rate information for developing lead equalization. If the aircraft has a HUD with a flightpath indicator, it will be possible for the pilot to estimate glideslope rate, and, hence, generate lead equalization. As will be shown, pilot lead equalization is not mandatory for closed-loop stability in this case.

The root loci for the glideslope loop closure with the three different pitch response-types are also presented in Fig. B-11. The root loci for the three response-types are similar indicating that the pitch response-type has no major influence on longitudinal path control. This is unlike the result for helicopters where pitch response-type does have an effect on position control.

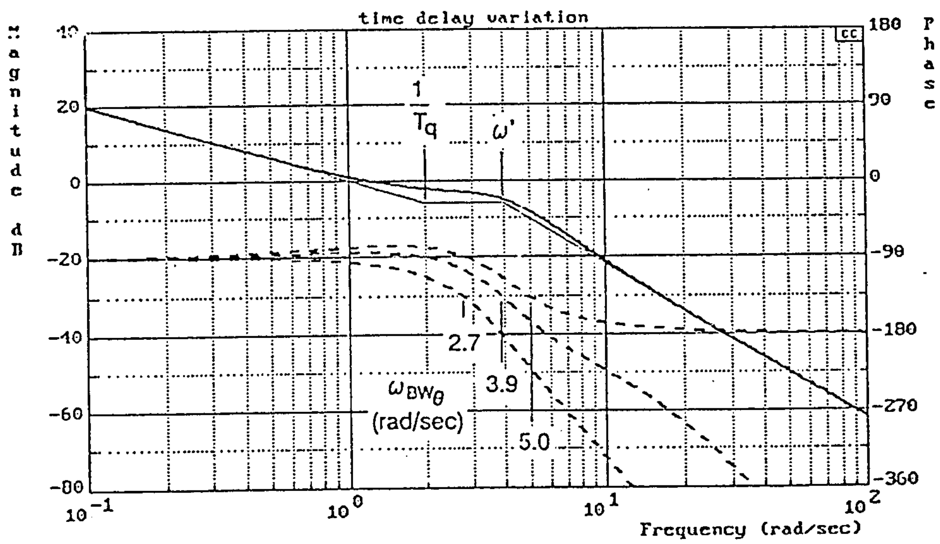
The pilot-vehicle analysis in Fig. B-11 indicates that there are no major benefits to be gained, in terms of pilot workload for longitudinal path control, by varying the pitch response-type. Accordingly, it may be assumed that there is no correlation between pitch response-type and visual cueing.

There are, however, some other factors that must be taken into account when considering the effect of pitch response-type on pilot workload. These factors pertain to the characteristics of the different response-types in long-term quasi-open-loop operations. In these situations, the different long-term control-response characteristics of these systems will impact pilot workload. For instance the self-trimming feature of the RCAH and Rate systems will most likely be preferred to the ACAH system that requires constant re-trimming as trim attitude is adjusted. These factors will be discussed in the next section of this Appendix where the effects of response-type and task on handling qualities are investigated.

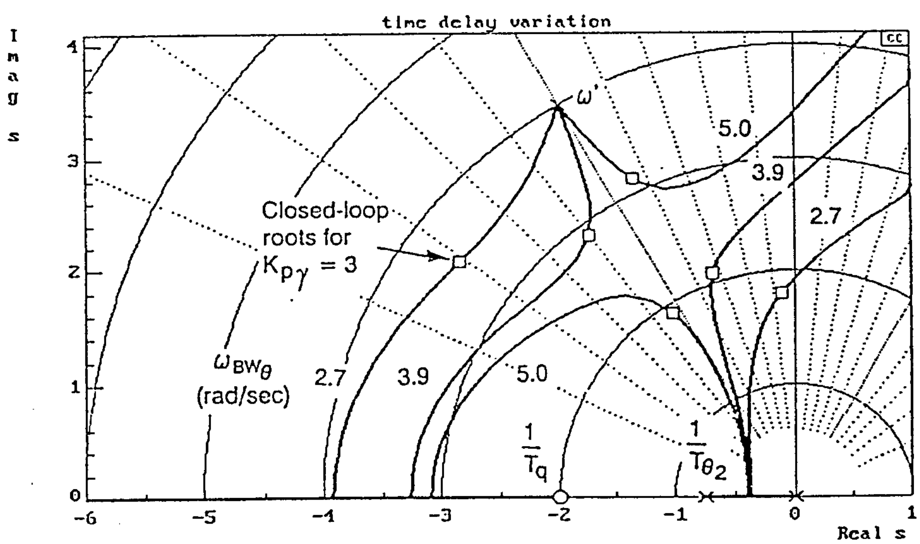
The pilot-vehicle analysis was also extended to investigate the effect of pitch bandwidth on the closed-loop flightpath response. The block diagram in Fig. B-12a illustrates the pilot-vehicle system and the root loci in Fig. B-12c illustrate the variation in the locus of the closed-loop flightpath mode with varying pitch attitude bandwidth using the RCAH response-type. The open-loop pitch attitude frequency responses (θ/δ_{es}) in Fig. B-12b show the variation in bandwidth for the three pitch configurations considered. Bandwidth is varied, in this example, by adding varying amounts of pure time delay to the basic pitch dynamics; the primary modes of the pitch response are not adjusted. The addition of pure time delay causes both bandwidth and time delay (as defined by the phase delay parameter, see Fig. B-6) to vary for the three pitch configurations.



a) Pilot-Vehicle Block Diagram



b) Pitch Attitude Response (open-loop)



c) Root-Locus for the Glideslope Loop Closure

Figure B-12. Effect of Pitch Bandwidth on Longitudinal Flightpath Control

The closed-loop modes for a fixed value of pilot gain are also displayed in Fig. B-12c to illustrate the benefits of greater pitch bandwidth on the closed-loop flightpath response. For the same amount of pilot gain, the greater bandwidth (and lower time delay) pitch systems allow the closed-loop flightpath response to be better damped and more stable. It follows, therefore, that the greater bandwidth (and lower time delay) pitch systems will allow the pilot to regulate flightpath more efficiently and with reduced workload (since the closed-loop response will be stable for a greater range of pilot gains). In high workload situations as will be encountered in flight in a degraded visual environment, higher bandwidth and lower time delay systems should improve handling qualities.

b. Lateral Flightpath Control

The effect of roll attitude bandwidth and time delay on horizontal flightpath control was also investigated using pilot-vehicle analysis techniques. For fixed-wing aircraft, the preferred roll response-type is Rate and the roll response dynamics may be assumed to consist of a roll subsidence mode ($1/T_R$) and time delay. The pilot-vehicle analysis is summarized in Fig. B-13.

For the purpose of this analysis, it was assumed that the pilot would directly regulate horizontal flightpath without explicitly regulating roll attitude as an inner loop. Under normal circumstances, when a clear horizon reference is discernible, a pilot would close (somewhat loosely) an inner roll attitude loop without incurring much workload. The approach taken in this analysis is to investigate the possibility of directly regulating horizontal flightpath, and, thereby, infer the attentional workload that is required for attitude control. If the analysis shows that direct control of horizontal flightpath is possible, it may be inferred that only loose regulation of roll attitude is required. Conversely, if direct control of flightpath is not possible, it may be inferred that the pilot must tightly regulate roll attitude at all times with a resulting increase in workload.

The analysis in Fig. B-13 investigates the effect of varying roll bandwidth and time delay on the piloted control of horizontal path. The block diagram (Fig. B-13a) indicates how the pilot may use both horizontal path and curvature information to control horizontal flightpath. The curvature information provides the lead compensation (through the look-ahead time T_G) that is essential for a stable closure of the flightpath loop. For this analysis, the frequency responses in Fig. B-13b show the variation in bandwidth in the three roll attitude configurations considered. As in the analysis of glideslope control (Fig. B-12), both bandwidth and time delay of the configurations are varied as $1/T_R$ is kept constant and pure time delay is added.

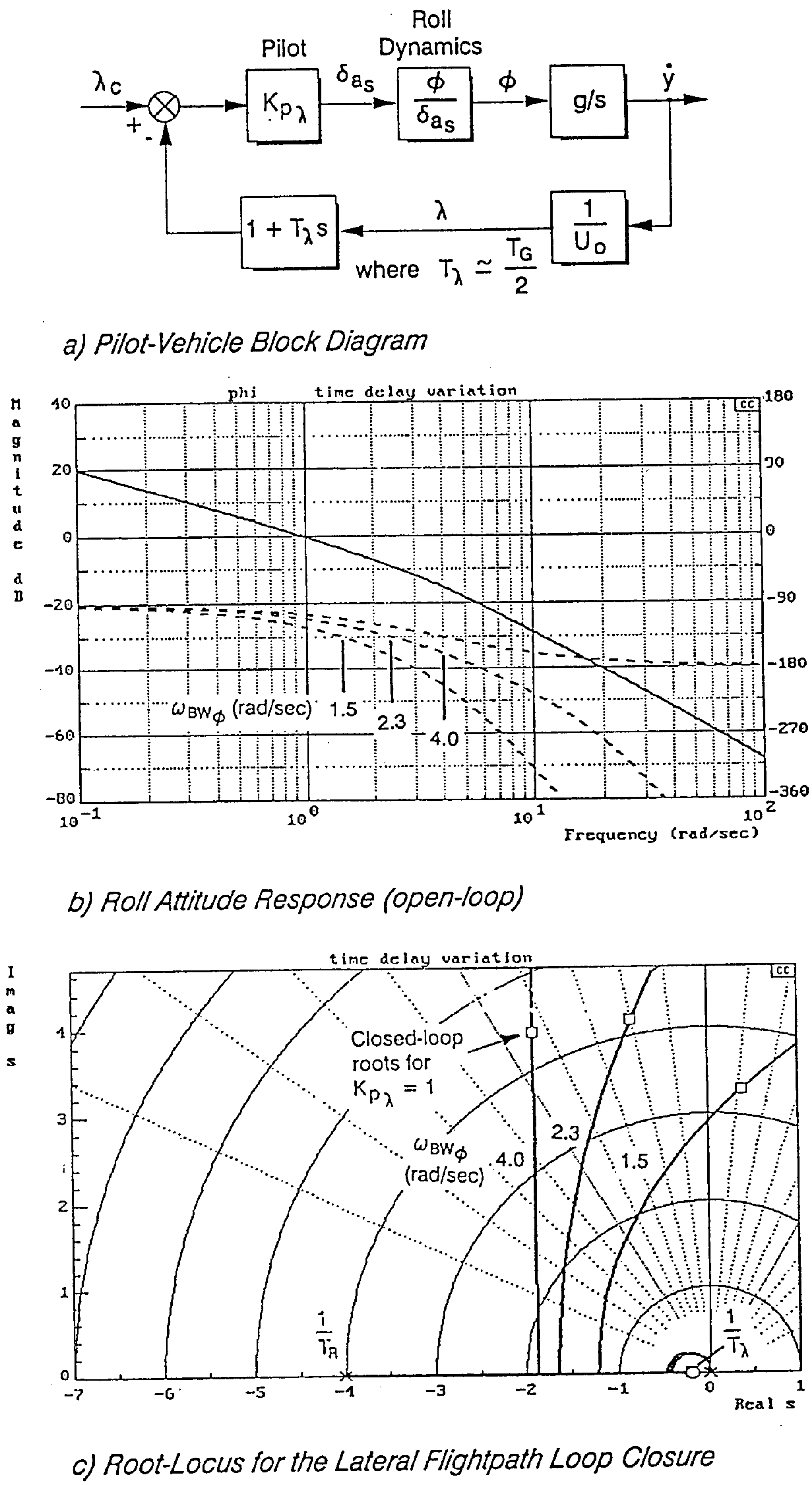


Figure B-13. Effect of Roll Bandwidth on Horizontal Flightpath Control

The root loci for the lateral flightpath loop closure in Fig. B-13c illustrate the effect of the roll attitude bandwidth and time delay on the closed-loop flightpath performance. Good visual conditions are assumed and the visual lead time constant (T_λ) is assumed to be 5 sec. This may be interpreted as a look-ahead time of roughly 10 sec. The locations of the closed-loop modes for a pilot gain of unity in all three cases are shown in Fig. B-13c. For the high roll bandwidth configuration, the primary closed-loop flightpath mode at this pilot gain is low-damped but stable. For the low bandwidth configuration, however, this pilot gain would cause a closed-loop instability. It is clear, therefore, that greater roll attitude bandwidth and lower time delay will benefit horizontal flightpath control.

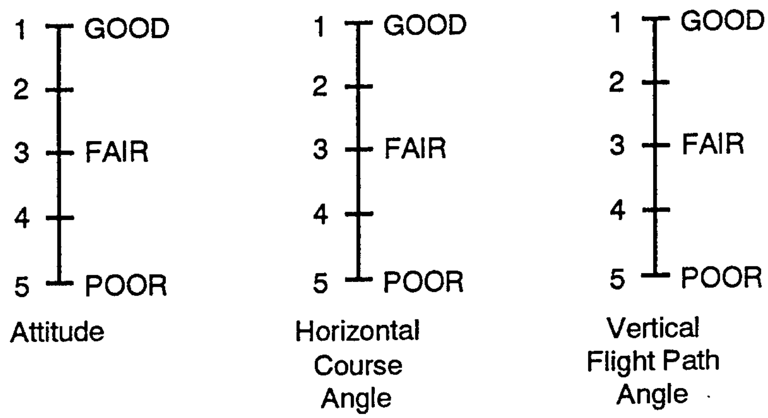
Stable closure of a direct lateral flightpath loop is possible only if there are adequate cues to estimate course curvature without undue pilot workload. In adverse visual conditions, the ability to judge curvature, and, therefore, to generate the necessary lead equalization, will be impaired. In these conditions, it will be necessary to regulate roll attitude more tightly as an inner loop to flightpath control. In addition, estimation of lead information from the limited look-ahead distance that is available will add to the pilot's perceptual workload and increase pilot time delay (Ref. B-24).

As the look-ahead distance decreases, the pilot will have to regulate roll attitude more tightly in order to ensure stable control of horizontal flightpath. The pilot workload involved in regulating roll attitude will be dependent on the roll attitude dynamics as determined by bandwidth and time delay. It may be inferred, therefore, that the handling qualities degradation due to the degradation in the visual environment maybe somewhat offset by improvements in the roll attitude dynamics.

It is possible that some of the added time delay and increased pilot workload experienced in a degraded visual environment may be offset by increased bandwidth and reduced time delay in the roll attitude dynamics. The increased bandwidth and reduced time delay will serve to increase the control margin available to the pilot.

5. A Proposed Visual Cue Rating Scale

A proposed visual cue rating (VCR) scale is presented in Fig. B-14. The scale is similar to that employed in the helicopter specification (Ref. B-2) with some modifications to account for the difference in the primary variables under the pilot's control (flightpath in fixed-wing aircraft versus position in helicopters). The scale reflects the fundamental cues that are required for precision operations in fixed-wing aircraft and are most likely to impact handling qualities. Other cues such as speed and range are not generally used in regular closed-loop operations. Speed is, however, integral to the flightpath cue.



DEFINITIONS OF CUES

X = Pitch or roll attitude and lateral course or vertical flight path angle

Good X Cues: Can make positive and precise X corrections with confidence and precision is good.

Fair X Cues: Can make limited X corrections with confidence and precision is only fair.

Poor X Cues: Only small and gentle corrections in X are possible, and consistent precision is not attainable.

Figure B-14. Suggested Visual Cue Rating Scale

The VCR scale should be used for assessing the external visual cue environment as well as any vision aid devices or displays that are used by the pilot to control attitude or flightpath. In order to separate the effect of the aircraft dynamics from the assessment of the visual cues, VCRs should be obtained using an aircraft with basic Rate response-type dynamics that have previously been assessed as being Level 1 in good visual conditions and negligible turbulence. Visual cue ratings must be obtained from several pilots over a range of appropriate tasks and there must be reasonable agreement between pilots. It is important to emphasize that the VCR scale is not purely an assessment of the outside visual scene (or the visual scene of a display or vision aid) but an estimate of the degree of confidence a pilot has in using the available cues for precision maneuvering.

The VCRs may then be used to assess the overall visual cue environment defined as the Usable Cue Environment (UCE). Figure B-15 shows a possible format for combining the VCR information and defining an UCE. It must be emphasized that Fig. B-15 simply speculates on the probable format for determining UCE. The actual form of Fig. B-15 may only be determined through simulation and flight tests.

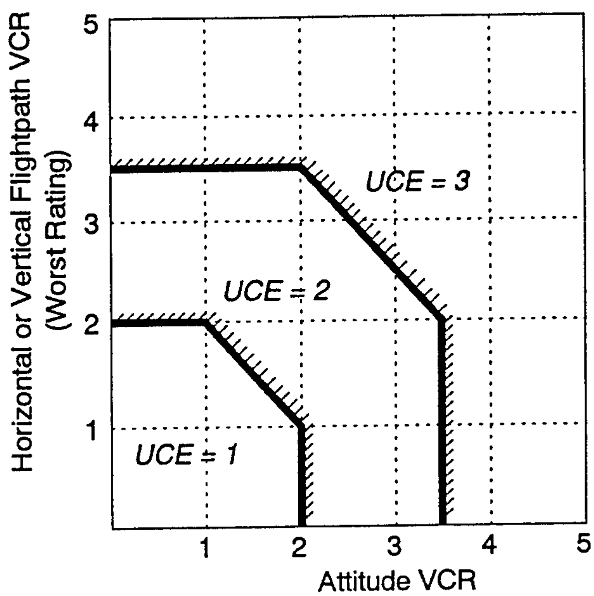


Figure B-15. Example Definition of the Usable Cue Environments

6. Effects of Visual Cueing on Handling Qualities Requirements

Experience with the helicopter handling qualities specification showed conclusively the tradeoff between dynamic requirements and visual environment. The pilot-vehicle analysis of flightpath control with fixed-wing aircraft, described above, indicates that there may be a similar interaction. Therefore, modification of some of the dynamic requirements in MIL-STD-1797A may be required to account for the effects of the visual environment. There is, however, no database currently available that will illuminate this subject and indicate what these modifications might be.

D. EFFECTS OF RESPONSE-TYPE AND TASK ON HANDLING QUALITIES

1. Results of Literature Review

There is a limited base of literature on night operations with fixed-wing aircraft that has resulted from the added capability that has been afforded by advanced night vision aids and tactics. A review of this literature base was undertaken in order to glean any information on aircraft response-type and task on handling qualities. The results of this review were previously presented.

The literature review did not uncover any information on the effect of response-type on handling qualities. This is largely due to the lack of diversity in response-types in current operational aircraft. The response dynamics of almost all current operational aircraft may be classified as Rate or Conventional response-types. The survey did indicate a significant influence of automatic modes, especially automatic

terrain following (automatic terrain avoidance) on pilot workload. These modes serve to relieve pilot workload in what is otherwise an extremely high workload environment.

For most MTEs, therefore, the required response-type will be Conventional or Rate. The exception will be the possible suitability of the ACAH response-type for landing. This is discussed in the following subsections.

Unconventional control modes such as the decoupled modes evaluated using the AFTI/F-16 aircraft may also be considered as candidates for response-type upgrades for specific MTEs. For example, the results of the AFTI/F-16 program (Ref. B-25) indicated that handling qualities benefits could be gained with the use of a direct sideforce (flat turn) mode for air-to-ground attack tasks. As these modes are unconventional and, in most cases, require specialized aerodynamic surfaces, they were not of primary interest for this study.

2. Example Task Where Response-Type Upgrade is not Needed: Terrain Following

There are several pitch response-types that are suitable candidates for terrain following. These include n_z-command, attitude command, rate command, and conventional response-types. Of these, rate command and conventional are presently used in aircraft that routinely perform terrain following missions safely. There is no information to indicate a preference for rate or conventional response-types for this type of task. At the relatively high expected frequencies of control in a terrain following task, it is likely that there will be no discernable difference between these two response-types.

Of the other response-types, attitude command has the advantage of precision flightpath control and pitch pointing but has the disadvantage of low agility and a requirement for constant pitch inputs or re-trimming. The high-gain feedback of attitude that is required for achieving attitude command generally restricts the amount of pitch control power that is available. The primary characteristic of attitude command is the proportionality between pitch attitude and stick force that can be an advantage in facilitating precision attitude control and, therefore, better flightpath control, but the requirement to constantly hold a stick force or re-trim will add to the pilot workload and may negate the benefits gained by precision pitch control.

Normal acceleration command (n_z-command) response-types are also in present use in a few aircraft. At low angles-of-attack, there are no appreciable differences between n_z-command and rate command response-types. At higher angles-of-attack, however, n_z-command becomes an angle-of-attack rate system and exhibits pro-stall tendencies. This characteristic of n_z-command systems has been identified in the

simulation studies of Refs. B-26 and B-27. The similarity between rate command and n_z-command at low angles-of-attack coupled with the undesirable effects of n_z-command at higher angles-of-attack indicate that there is no clear advantage to be gained by using n_z-command in a terrain-following task.

For terrain following, therefore, there is no evidence to support a requirement for response-type upgrade with a degradation of the visual environment.

3. Example Task Where Response-Type Upgrade is Required: Precision Landing in Low Visibility

In any piloting task requiring navigation with reference to objects on the ground, the ability to clearly judge forward transnational and vertical rates is critical. Based on the discussion in Section C, it would be expected that increased inner-loop stabilization would reduce the pilot's mental workload and therefore improve overall handling qualities. As was shown above for the terrain-following task, this is not always the case.

An increase in response-type is beneficial, however, in mission task elements where there is a greater need for a stable aircraft. The single mission element that has been studied extensively is the precision landing in conditions of low visibility. In such a situation, the increased pilot workload involved in attempting to perceive motion and process the perceived information will result in a degradation in overall handling qualities.

The simulation experiment of Ref. B-6, discussed in Section B, shows evidence of the advantages of an improvement in response-type for landing. Although this simulation, conducted on the NASA Langley Research Center's Visual/Motion Simulator, was not specifically intended to evaluate response-types in conditions of reduced visibility, it had the effect of doing so. The field of view and scene details on the camera/terrain-board/CRT arrangement reduced the outside visual cueing. Some compensation was provided by a head-up display that included a pitch ladder and flight path vector symbol.

The pilot ratings from Ref. B-6 were shown in Fig. B-3. The ratings illustrate the improvement in handling qualities achieved by both attitude command and flightpath command systems over rate command. Performance measures taken in the simulation further supported this improvement. As an example, Fig. B-16 shows the cumulative percentage curves for touchdown sink rate and touchdown position for the four response-types evaluated: flightpath command/flightpath hold (GCGH), attitude command/attitude hold (ACAH1), rate command/attitude hold (RCAH2), and pseudo-flightpath command/attitude hold (GCAH4). Figure B-16a shows data when autothrottles were not available, and Fig. B-16b shows data when autothrottles were on.

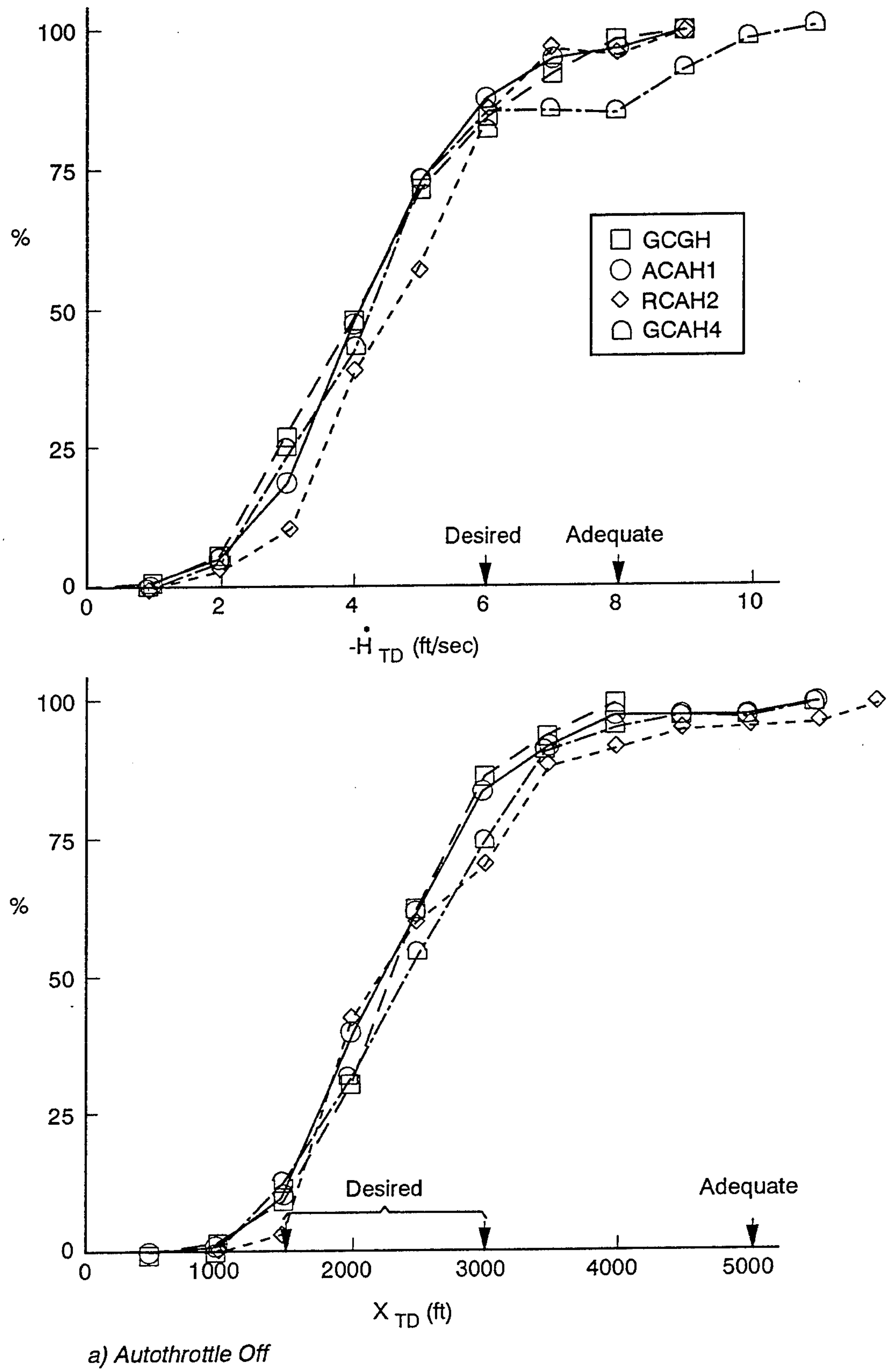
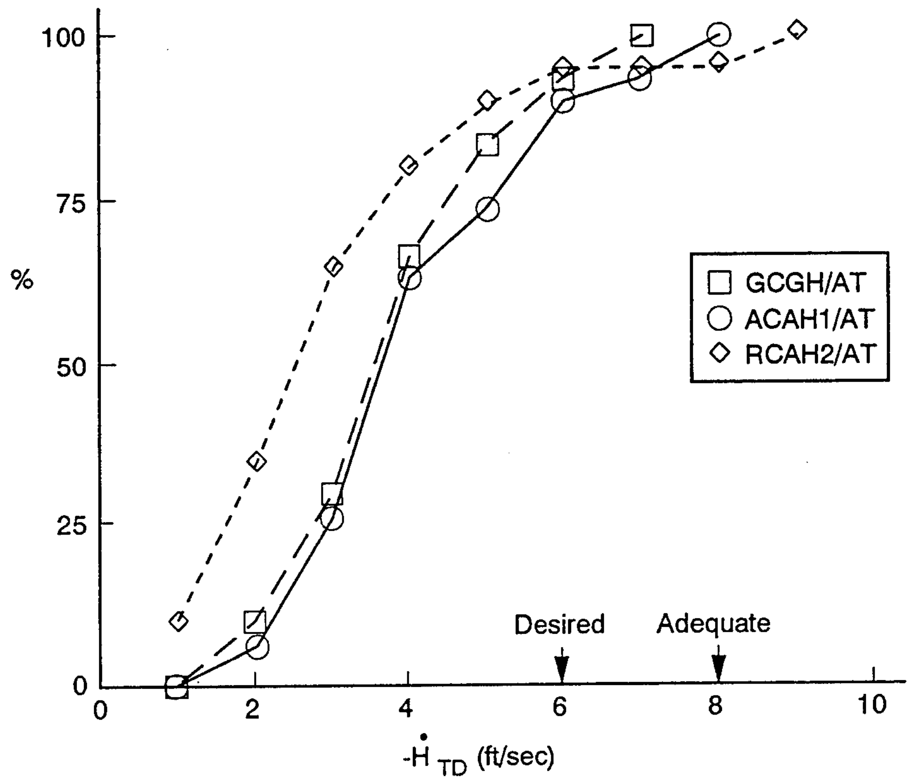
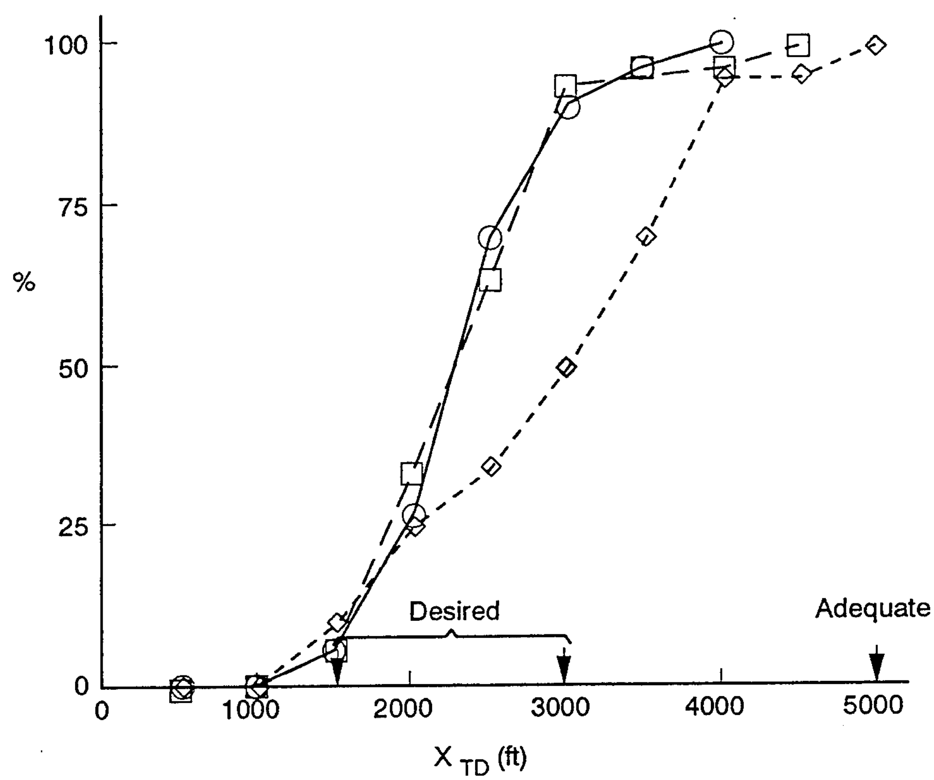


Figure B-16. Cumulative Percentage Curves for Sink Rate and X-Distance at Touchdown from Simulation of Ref. B-6





b) Autothrottle On

Figure B-16. Cumulative Percentage Curves for Sink Rate and X-Distance at Touchdown from Simulation of Ref. B-6 (concluded)

The cumulative percentages represent the percent of landings that were at or below the specified value; for example, if a line goes through 50% at -4 ft/sec touchdown sink rate, this indicates that 50% of the landings were at sink rates of 4 ft/sec or less. As Fig. B-16a shows, there were more hard landings with the rate command system (the percentage line for sink rate is shifted to the right compared to the other systems) even though there was also a tendency to land long (the touchdown position line is also shifted right at the higher percentages). When autothrottles were available, Fig. B-16b, the touchdowns were much softer with rate command, but at the expense of much longer touchdown distances. It was easy to over-rotate with rate command, resulting in a floating down the runway; eventually a landing was achieved, at very low sink rates, but only after much of the runway was used up. With or without autothrottles, there was a definite degradation overall with rate command when compared to the other response-types.

4. Proposed Response-Type Requirements

The proposed framework for integrating MTEs with required response-type and usable cue environment (UCE) is presented in Table B-3. Due to lack of supporting data on the subject, Table B-3 is restricted and presented only as an example to illustrate the means by which these elements may be integrated.

TABLE B-3. REQUIRED RESPONSE TYPES

MTE	UCE = 1		UCE = 2		UCE = 3	
	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
Precision Landing	Rate	Rate	ACAH	Rate	GCGH	ACAH
In-Flight Refuel as receiver	Rate	Rate	ACAH	Rate	ACAH	TBD
Terrain-Following	Rate	Rate	Rate + ATF	Rate	TBD	TBD

Rate – Rate or Rate Command/Attitude Hold (RCAH) response-type (includes Conventional)

ACAH – Attitude Command/Attitude Hold response-type

GCGH – Vertical Flightpath Command/Flightpath Hold (γ-Command/γ-Hold)

ATF – Automatic Terrain Following

All the MTEs proposed for the updated Flight Phase Categories, listed in Table B-1, should eventually be included in Table B-3. The table may be expanded as, and when, supporting data on the handling qualities implications of response-type and visual environment in the performance of these MTEs become available.

E. CONCLUSIONS

This Phase I effort investigated the effect of interactions between the pilot's visual cue environment, the aircraft response-type, and piloting task on handling qualities. The two major objectives of the study were to:

1. Create the structure, format, and methodology to incorporate these interactions into a mission-oriented specification; and
2. Generate the basic tables relating these elements, to the extent possible, based on available test data.

Both these objectives have been met, to the extent possible. Definitive conclusions could not be drawn, however, due to a lack of supporting handling qualities data.

A framework for incorporating response-type, visual environment, and task in a mission-oriented handling qualities specification was proposed with identified gaps to be filled in as, and when, data becomes available.

Attitude and flightpath (vertical and horizontal) cues were identified as being fundamental to visual flight. These cues may be derived from the outside scene, a representation of the outside scene using sensors, or directly provided in the form of symbology that is either projected on the visual scene or representation, or provided on a different display.

A closed-loop pilot-vehicle analysis of the effects of pitch response-type on piloted control of longitudinal path showed that response-type does not play a significant role in the piloted control of flightpath. Data from a simulation experiment using an approach and landing task indicated, however, that there are potential handling qualities benefits to be gained for this task by upgrading the pitch response-type.

A closed-loop pilot-vehicle analysis of the effect of pitch and roll bandwidth and time delay on the piloted control of vertical and horizontal flightpath, respectively, indicated that the pilot effort required

for path control may be reduced by increasing the bandwidth and reducing time delay. Handling qualities in a degraded visual environment may, therefore, benefit from improved pitch and roll dynamics.

A review of available literature on night operations using a variety of visual aids yielded no specific handling qualities information but indicated the strong role of automatic modes in alleviating pilot workload.

F. RECOMMENDATIONS FOR FUTURE WORK

The Phase I investigation developed a framework for incorporating response-type, visual cueing, and task, in a mission-oriented handling qualities specification. Complete development of these concepts was not possible due to the lack of supporting data. Future work in this field should, therefore, focus on generating the supporting data that is required to fully develop these concepts.

Specific recommendations for future work are presented below:

1. Perform a detailed assessment of the environment in night ground attack
   - has the highest potential for some relief from advanced response-types
   - visit operational or training bases and interview pilots about night attack missions
   - determine if there are significant differences between aircraft for the task (specifically related to handling qualities)
2. Investigate interactions between visual cues, response-types, and MTEs
   - conduct piloted simulation with variations in visual cues from good to poor
   - simulate NVG, Flir, night visual scenes (such as was done in the Ref. B-28 investigation)
   - focus on tasks normally flown in low visibility or at night
   - include some variation in bandwidth and phase delay, along with response-type
   - obtain VCRs to refine VCR scale and procedures and begin to assemble UCE requirements

3. Perform flight experiments to verify major simulation results

   - look at the most critical combinations of response-types, MTEs, and visual cue environments

   - Use a variable stability aircraft with simulated NVGs or another means of progressively degrading visual cues

4. Construct detailed requirements for MIL-STD-1797A

   - determine final VCR scale and UCE limits

   - develop a list of MTEs for which the scale is applicable

   - develop a table relating MTE and UCE to required response type

   - develop handling qualities boundaries based on UCE

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APPENDIX C

DEMONSTRATION MANEUVERS FOR ADVANCED FLIGHT CONTROL CONFIGURATIONS

A. BACKGROUND AND PURPOSE

1. Background

a. The Need for Demonstration Maneuvers

There is an ongoing effort to refine the military standard for flying qualities of aircraft, MIL-STD-1797A (Ref. C-1), into a more mission-oriented document. A mission-oriented standard will provide direct feedback to all members of the user community, including both designers and procuring activities, of the interactions between the dynamic requirements and the pilot's operating environment, including visual information (Refs. C-2 and C-3).

Despite this revision of MIL-STD-1797A, it is recognized that the specification of flying qualities in a single reference specification may never be complete. Advances in flight control systems, cockpit controllers, and aircraft effectors, may always outpace the advances in flying qualities criteria. In addition, some deficiencies in flying qualities, such as pilot-induced (or pilot-in-the-loop) oscillations (PIOs), may not always be exposed by the criteria in MIL-STD-1797A or in use elsewhere. Finally, since the requirements in the standard are intended to be applied to one axis at a time, there are no catch-all criteria that assure that multiple-axis operations will be acceptable.

The final verdict on the suitability of a prototype aircraft design must come from piloted evaluations. Unfortunately, there is no uniform set of published maneuvers to guide the evaluations. In fact, in the acquisition and acceptance testing of new military aircraft, formal pilot-in-the-loop flight testing is seldom conducted by the Air Force, because there is no *contractual* requirement to do so. In the past, flight testing for "flying qualities" has consisted mostly of open-loop steps and doublets to verify dynamic characteristics against quantitative requirements taken from the military specifications. Typically, if closed-loop flight testing, such as Handling Qualities During Tracking (HQDT), is conducted it is introduced to the development process only after the prototype is flying. The apparent imposition of real closed-loop testing at this point has sometimes appeared to the manufacturer to be almost arbitrary, often unannounced, and always unnecessary. Since the original flying-qualities specification didn't require closed-loop testing, the manufacturers might say, it should not be performed. This has often resulted in an almost confrontational atmosphere between the procuring activity and the builder.

The only way to assure that pilot-in-the-loop testing is a) performed, b) performed to a consistent standard of judgment, and c) required from the beginning, is to include the maneuvers and their definitions in the flying qualities specification. These maneuvers then become a standard part of all future procurements.

b. Experiences with the Rotorcraft Specification ADS-33C

Lack of a specific set of demonstration maneuvers for handling-qualities testing has not been limited to fixed-wing aircraft. It was recognized by the U.S. Army in the 1980s that such a set of maneuvers was needed for helicopters. This has led to an extensive series of simulations and flight tests to clearly identify the maneuver definitions and their performance requirements.

In the current U.S. Army specification for flying qualities of military rotorcraft (Ref. C-4), a significant portion of the document is devoted to definition of 15 flight test maneuvers. At this writing ADS-33C is undergoing revision for adoption as a tri-service standard (Ref. C-5) and this version will have 26 maneuvers. These qualitative flight test maneuvers are an integral part of the specification; throughout the quantitative portion, all requirements are referenced to only these 26 maneuvers and no others. The maneuvers represent a necessary compromise between a formal definition of all possible task elements of the aircraft and tasks that were found to be easily tested in flight. Therefore, they are *not* a substitute for meeting the quantitative criteria. There is no allowance made for failing the quantitative criteria but passing the qualitative.

The demonstration maneuvers in ADS-33C were designed and refined with the cooperation of the sponsors of the specification (the Army Aeroflightdynamics Directorate of the Aviation and Troop Command), the Army's test branch (the Airworthiness Qualification Test Directorate at Edwards AFB), other outside participants including the Canadian Institute for Aerospace Research, and many of the helicopter manufacturers themselves. These maneuvers are, as a result, a culmination of a collaborative effort.

Experience with the development of the rotorcraft flight test maneuvers helped in conducting the study documented in this Appendix. It is also hoped that a similar cooperative approach can be established as the formal demonstration maneuvers are defined and finalized.

2. Purpose of This Study

This Appendix documents the results of a study performed under sponsorship of a Phase I Small Business Innovative Research (SBIR) contract from the U.S. Air Force. The objective of this Phase I study has been the review of candidate flight test demonstration maneuvers and definition of tentative performance limits for the most promising of the maneuvers. In conducting this study many of the past flight and simulation research reports from the U.S. Air Force and other sources have been reviewed. Focus has generally been limited to the past twenty years or so — since the development and full use of the modern Cooper-Harper Handling Qualities Rating (HQR) scale (Ref. C-6) and the accompanying definitions of desired and adequate performance levels. Also, the emphasis has been on maneuvers that require high levels of manual piloted control and that are, therefore, subject to discussion and controversy. Maneuvers for more benign mission elements — such as cruising flight, climbs, and descents — will be required, but these are expected to be much less volatile. The performance requirements for such maneuvers will come from other sources, and they were not a primary focus of this study. It is proposed that development work be conducted in a follow-on Phase II effort.

The maneuvers were judged on the basis of several different evaluation factors, as follows:

- *Applicability to specific mission task elements.* A significant new development in the mission-oriented standard will be the incorporation of mission task elements that directly reflect the operational missions of current and future aircraft. A proposed categorization of these mission elements, divided on the basis of requirements for precision and aggressiveness, was developed in Ref. C-2 and is shown in Table C-1. The objective of the current study, therefore, has been the definition of flight test maneuvers that directly relate to the mission task elements of Table C-1.

- *Requirements for piloted control.* As indicated above, the ultimate goal of a mission-oriented standard should be to define a maneuver corresponding to every mission task element. Because of the scope of this Phase I effort, it was decided that the primary focus would be limited to those tasks that require a high level of closed-loop piloted control. This essentially means that tasks listed in the leftmost column of Table C-1 (Non-Aggressive, Non-Precision tasks) were not considered in this study. Maneuvers should be developed for these mission elements, or they should be considered candidates for deletion from Table C-1.

- *Ease of flight testing.* Some maneuvers will be inherently hazardous for a new prototype design; for example, aerial refueling or precision landings will probably always be approached in a build-up program, rather than attempting the final maneuver on first flight. Others may be impractical from either a logistics or schedule standpoint; for example, 1-vs.-n (where n is a very large number) air combat may be a primary mission of a particular design, but it is nearly impossible to devise a maneuver, with well-defined performance levels, for such a scenario. Similarly, beyond-visual-range combat with an advanced "smart" missile may be a requirement, but the success of a

TABLE C-1. CATEGORIZATION OF MISSION-TASKS-ELEMENTS

CATEGORIZATION OF MISSION-TASK-ELEMENTS			
Non-Precision Tasks		Precision Tasks	
Non-Aggressive (Category B)	Aggressive (Category D)	Non-Aggressive (Category C)	Aggressive (Category A)
Reconnaissance (RC)	Gross acquisition using loaded roll	Aerial recovery (AR)	Tracking maneuvering target (CO)
In-flight refueling - tanker (RT)	Missile defense with loaded roll	In-flight refueling as receiver (RR)	Ground attack (GA)
VMC and IMC loiter/cruise/ climb/descent (including emergency descent) (LO, CR, CL, D, ED, DE)	Anti-submarine search and maneuvering (AS)	Low altitude parachute extraction (LAPES)	Weapon delivery and launch (WD)
Normal takeoff (TO)	High speed max g turn	Catapult takeoff (CT)	Terrain following
Waveoff/go-around (WO)	"Herbst" turn	Approach (PA)	"Herbst" turn
Non-precision landing (L)	Split S, chandelle, hammerhead turn, loop, barrel roll, snap roll, etc.	Precision landing	Precision aerobatics, e.g., 8 point roll, etc.
	Scissors, high and low speed "yo-yo"	Close formation (FF)	
		Tactical final approach	

flight demonstration will be highly dependent upon the maturity of the missile system, and therefore this is not a very good candidate for flight testing. Most maneuvers that fail this criterion fall more into the category of performance or mission suitability tasks, rather than handling qualities evaluation tasks.

- *Ability to define the task and constrain performance.* This is simply an adjunct of the preceding objective: maneuvers that are easily flight tested will be those for which the task scenario is repeatable and performance limits are definable. In the analysis of candidate maneuvers, it was found that many of the one-on-one air combat tasks used in flight research programs tend to suffer from these deficiencies. This is discussed in more detail in the next section.

- *Coverage of all levels of maneuver amplitude.* Most of the requirements of MIL-STD-1797A, and most of the flying qualities tasks in use today, emphasize small-amplitude control. This certainly makes sense, since problems endemic to modern aircraft will typically be exposed by such tasks. There is, however, a need to assure that the moderate- and large-amplitude characteristics of current and future aircraft are also acceptable. While there are some requirements (dealing with, for example, control force per g, time to roll through a specified bank angle, etc.), there are not as many maneuvers. As this study has confirmed, there is a shortage of tasks that emphasize maneuvering at elevated load factors or that involve g capture or large rolling maneuvers. These types of tasks will be especially challenging in defining performance criteria that are both meaningful and measurable. As this study shows, more work is clearly needed.

- *Adaptability to all aircraft classes, response-types, and levels of visual cues.* A common criticism of the current MIL-STD-1797A is that it has a "fighter bias," since almost all of the quantitative criteria were developed for, and apply primarily to, fighters. There have been steps taken to remedy this (including development of pitch attitude and flightpath response requirements for transports in Ref. C-2). The demonstration maneuvers must also reflect all classes of aircraft. In some cases, of course, the specific mission task element relates to a specific class of aircraft; for example, tracking a maneuvering target would not be expected to apply to transports. On the other hand, some tasks may apply to all classes, including not only the obvious, such as landing, but the less apparent, such as in-flight refueling as the receiver.

After a list of maneuvers meeting these criteria was assembled, an attempt was made at defining desired and adequate performance limits for each candidate maneuver. In some cases these limits are reasonably well defined for at least one aircraft class. In other instances, however, little is known about what might constitute reasonable expectations for performance. The gaps in knowledge are identified in this report. The ultimate goal of this effort, including possible Phase II and III research and development, will be a truly mission-oriented set of demonstration maneuvers: every mission task element referred to in the body of MIL-STD-1797A will have a specific maneuver that directly relates to it. If successful, there will be no mission task elements for which maneuvers are not specified.

Finally, a recommended series of simulation and flight research experiments is given to fill in the most obvious gaps in the definitions of the demonstration maneuvers.

3. Maneuvers Contained in Proposed Revisions to MIL-STD-1797A

During the course of this study, a set of proposed revisions to MIL-STD-1797A was released for industry review. Included in the proposed revisions are several of the flight test maneuvers analyzed here. Therefore, it was decided that, although a final judgment has not been made at this time on whether to

adopt the revisions to 1797A, the maneuvers should be included in the current study. They are considered to be simply another source of information for this report.

4. The Structure of the Demonstration Maneuver Set

For any maneuver to be considered a candidate demonstration maneuver, it was considered imperative that a clear set of objectives be defined for that maneuver. In addition, the method for performing the task itself must be described unambiguously, and finally the performance standards must be clearly called out. This led to a structure that parallels that adopted for the maneuvers in the helicopter specification. For a demonstration maneuver to be of value, the following four elements of its description must be defined: objectives, description of maneuver, desired performance, and adequate performance. This structure is followed for the candidate demonstration maneuvers listed in this report.

This structure differs slightly from that used in defining the Standard Evaluation Maneuver Set (STEMS) in Ref. C-9, where additional information on applicable aircraft Classes and Flight Phase Categories, performance objectives, aircraft attributes, and operational applications were specifically called out. The effects of aircraft Class are covered in the demonstration maneuvers through the definition of the performance limits; the other information will be addressed in the statement of objectives for each maneuver. Since the ultimate goal of this work is to create a parallel structure between the quantitative requirements of MIL-STD-1797A — where specific MTEs are referenced — and the qualitative demonstration maneuvers, the relevance of certain aircraft attributes and operation applications will be obvious. For example, in the mission-oriented standard, requirements on roll response in aggressive maneuvering will correspond directly to a specific subset of the demonstration maneuvers that will include tracking a maneuvering target but not in-flight refueling (as either tanker or receiver), since the latter does not involve aggressive maneuvering.

5. Outline of this Report

Section B contains the "meat" of this Appendix. There, all of the candidate maneuvers, their sources, and experiences in applying them, are discussed. Section C summarizes the maneuvers considered sufficiently mature to take on to further development. Finally, Section D defines the simulation or flight research programs required to refine the maneuvers to assure that they are ready for incorporation into a future version of the military standard.

B. DETAILED REVIEW OF MANEUVERS CONSIDERED

1. Non-Aggressive, Non-Precision Up-and-Away MTE (Part of New Category B)

The MTEs that fall into this category (as listed in Table C-1) are the following:

- Reconnaissance
- In-flight refueling — tanker
- VMC and IMC loiter/cruise/climb/descent

These MTEs are comprised of basic maneuvers that must be performed by all classes of aircraft; i.e., they involve climbs, descents, turns and level flight. The other tasks that fall into this category are landings and takeoffs that are discussed in the next subsection. In general, the MTEs listed above are relatively benign tasks that do not emphasize closed-loop pilot activity. Instead, they are tasks that, ideally, are performed with a minimum of pilot effort. This will ensure that the pilot has sufficient capacity to perform the other procedural tasks, such as communication, navigation, and threat avoidance, that are necessary in these flight phases. For this to be true, the response characteristics of the aircraft in these flight phases must be such as to allow the pilot to relinquish control for short periods of time without encountering large excursions in flightpath. In other words, the response characteristics of the aircraft must allow the pilot to attain the desired performance objectives in these tasks with a tolerable workload while operating in a divided-attention environment.

The primary aircraft dynamic modes that have the potential to influence the pilot workload involved in the performance of these tasks are the low-frequency spiral and phugoid modes, and, possibly, the dutch roll mode. In modern aircraft with full-time augmentation, the significant dynamic modes will be the augmented equivalents of these modes. The desired characteristics of these modes (frequency, damping, and time constants) are specified in MIL-STD-1797A (Ref. C-1). All are usually considered "nuisance" modes, meaning they are not difficult for the pilot to suppress and they do not have direct bearing on the effectiveness of a particular design for short-term operations. If an aircraft meets the Level 1 requirements for these modes in Ref. C-1, it is likely that the aircraft will be able to perform the MTEs listed above with a minimum of pilot workload. The maneuvers are not, therefore, considered to be particularly difficult or discriminating in terms of overall handling qualities.

Most often, especially in current and future aircraft, these MTEs will be performed by the autopilot (automatic flight control system (AFCS)) with the pilot acting simply as the instigator and monitor. With a well-designed AFCS, divided-attention operations with tolerable pilot workload are possible as evidenced

by the widespread use of the autopilot. The value of demonstration maneuvers for these flight phases or tasks is that they will provide a clear, repeatable, and quantifiable procedure for evaluating the handling qualities of an aircraft in these very basic maneuvers.

Before the use of the Cooper-Harper Handling Qualities Rating scale for evaluating handling qualities, tasks such as climbs and descents were used for handling qualities evaluations in flight research programs. Typically, these tasks were not clearly defined and did not have any performance objectives that could be used to judge and quantify task performance. The purpose of these tasks, in the early research programs, was to evaluate the aircraft qualitatively. Reference C-7 provides some insight into the use of these tasks for handling qualities evaluations. In the flight research program of Ref. C-7 (using the XB-70 aircraft) the handling qualities of the aircraft were evaluated using a series of maneuvers including altitude changes and level-flight turns. A handling qualities rating scale was used but since it did not include judgement of performance in any quantitative manner, performance objectives were not included as part of the task assessment.

Demonstration maneuvers with clearly defined and repeatable maneuvers and clearly defined performance requirements can be used to conclusively demonstrate if an aircraft is capable of performing these MTEs satisfactorily. It is likely that these demonstration maneuvers will be sufficiently benign for all aircraft to be able to perform them to the desired performance standards with ease. This is not a concern, however, as the intent of these maneuvers is to provide clearly defined and repeatable procedures for evaluating an aircraft throughout its operational envelope for all appropriate MTEs.

a. <u>Relationship to Automatic Flight Control Systems Requirements</u>

Defining demonstration maneuvers for the MTEs listed above is relatively straightforward. There is, however, no clear basis on which to judge performance as these tasks have not been evaluated in the past with any specific guidelines. The most suitable locations to begin a search for guidance on performance objectives for these types of tasks are design specifications for automatic systems.

The MTEs listed above emphasize basic maneuvers such as level flight and capturing and maintaining altitude, altitude rate, heading, and airspeed. In modern aircraft, these functions are most often performed by the automatic flight control systems that have been specifically designed to perform these capture and hold functions. Requirements that define the desired performance for the AFCS in the performance of these functions are outlined in the military specification governing the design of flight control systems, MIL-F-9490D (Ref. C-8).

A primary goal in the design of automatic flight control systems is that it perform in a manner equivalent to a skilled pilot. In other words, the actions of the autopilot system should mimic the actions of a skilled pilot. This ensures pilot acceptance of the automatic systems and minimizes the pilot workload involved in monitoring the operation of these systems. It is sensible, therefore, to use the performance objectives for the design of automatic systems as preliminary performance requirements for related demonstration maneuvers.

b. Definition of an Example Demonstration Maneuver

As an example of a demonstration maneuver for this category of MTEs, the requirements for altitude, airspeed, and heading hold as stated in Ref. C-8 may be used as the desired performance criteria for a demonstration maneuver for straight and level flight in fully-attended operations. For divided-attention cruising flight, tentative performance limits may be defined based on expectations for instrument flight in the civil sector.

Precision level flight (VMC or IMC).

a. Objectives.
   - Check ability to maintain altitude, airspeed, and heading in cruise.
   - Check basic stability in conditions typical of divided-attention operations.

b. Description of maneuver. Initiate the maneuver at a target altitude, airspeed, and heading in straight and level flight. Automatic flight control functions may be used if they are normally available in cruise conditions. Otherwise, perform maneuver with all automatic flight ("hold") functions OFF. For divided-attention operations, a secondary, non-piloting task will be performed by the pilot flying. This task should be representative of those normally encountered, but it may be modified to suit the task requirements. Preferable divided-attention tasks include copying of an instrument clearance and manual mapping of the flight route on aviation charts. Since the task emphasizes low-frequency operations, a minimum time limit of several minutes (nominally around ten) should be established.

c. Desired performance.
   1. Fully attended operations.
      - Maintain altitude within ±30 ft.
      - Maintain airspeed within ±5 kt or 2% of the trim airspeed.
      - Maintain heading within ±3 deg.
   2. Divided-attention operations.
      - Maintain altitude within ±50 ft.
      - Maintain airspeed within ±10 kt.
      - Maintain heading within ±3 deg.

d. Adequate performance.

1. Fully attended operations.

- Maintain altitude within ±60 ft.
- Maintain airspeed within ±10 kt or 4% of the trim airspeed.
- Maintain heading within ±6 deg.

2. Divided-attention operations.

- Maintain altitude within ±100 ft.
- Maintain airspeed within ±15 kt.
- Maintain heading within ±6 deg.

This is only an example of an MTE for cruising flight. Work still must be done to refine the task and the performance numbers for this MTE. This work, and the complete development and refinement of further maneuvers to evaluate these MTEs, is left to Phase II of this effort.

2. Non-Aggressive, Non-Precision Terminal MTE (Remainder of MTE in New Category B)

The MTEs that fall in this category in Table C-1 are:

- Normal takeoff
- Waveoff/go-around
- Non-precision landing

As with the MTEs discussed above, these MTEs are also comprised of basic maneuvers that must be performed by all classes of aircraft. In contrast to the maneuvers discussed above, however, these maneuvers are not usually performed by an autopilot and generally involve a greater degree of closed-loop pilot operation. Nonetheless, the non-aggressive nature of normal terminal area operations will allow quasi-open-loop operation for the majority of the tasks.

In terminal area operations, the necessary division of attention required of the pilot is significantly increased. This is due to the increased navigational and communication workload that, when combined with other tasks such as traffic and terrain avoidance, serve to distract a pilot from the primary task of flying the aircraft. As was discussed for the up-and-away MTEs, the need for divided attention operation places requirements on the aircraft response characteristics in these flight phases. The aircraft response characteristics in these flight phases must be stable and predictable enough to allow unattended operation for short periods of time with no undesirable deviations in flightpath. If the response characteristics are not predictable, the pilot will have to focus specifically on the task of flying and reduce attention to the other tasks that are necessary in terminal area operations.

As in the up-and-away MTEs discussed above, the aircraft response characteristics that will have the greatest influence on the handling qualities in these terminal area MTEs will be the low-frequency modes (phugoid, spiral, and dutch roll). In some instances, such as takeoff and the landing flare, the short-term longitudinal response characteristics will also be a factor.

Because of the importance of terminal area operations for all aircraft types, these tasks have been used extensively as handling qualities evaluation tasks in past flight research and test programs. These tasks are a necessary part of any flight profile and are important for evaluating operational safety aspects. Typically, however, the evaluations using these tasks under "normal" (non-precision) operating conditions in previous flight test and research programs have been performed in a qualitative manner with no specific maneuver guidelines or performance constraints. There is no available handling qualities database for these tasks.

As for the up-and-away MTEs under Category B, demonstration maneuvers can be used to standardize these tasks with specific performance constraints that would allow quantitative judgement of the handling qualities. For example, a less aggressive version of the lateral offset landing task (discussed later) can be used as a demonstration maneuver for non-precision landings. The task can be made less aggressive by increasing the altitude at which the offset correction is made and by reducing the magnitude of the offset. These parameters would be adjusted to represent those typically encountered during landing approaches to current commercial and military airfields.

The performance constraints for a non-precision offset landing task can be derived from the requirements for the precision offset landing. Due to the reduced urgency and, hence, the reduced level of aggressiveness required for these operations, the desired performance requirements for this task may simply be the adequate performance bounds for the precision task.

3. Aggressive, Non-Precision MTEs (Category D)

The MTEs that fall into this category are listed below.

- Gross acquisition using loaded roll
- Missile defense with loaded roll
- Anti-submarine search and maneuvering
- High-speed max-g turn
- "Herbst" turn
- Split S, chandelle, hammerhead turn, loop, barrel roll, snap roll, etc.
- Scissors, high and low "yo-yo"

All the MTEs in Category D are up-and-away tasks. These tasks generally emphasize large-amplitude maneuvering with special emphasis on flightpath control (vertical and horizontal). Several involve load factor (g) and attitude captures, while others, such as gross acquisition, involve pointing at a target. The primary aircraft-related characteristics that play a significant role in the performance of these tasks are the vertical and horizontal flightpath responses.

a. Gross Acquisition Tasks

Gross acquisition tasks have been included in several flight research programs and these provide a suitable starting point in the search for demonstration maneuvers that will satisfactorily evaluate the essential aircraft handling qualities that affect the performance of these MTEs. A compilation of these past experiences is provided in Table C-2.

Table C-2 lists the target tracking tasks that have been used in previous flight research programs performed primarily by Calspan Corporation and the Air Force Test Pilot School (TPS). The target tracking tasks listed in Table C-2 were usually differentiated into a gross acquisition segment followed by a fine tracking segment. Different performance bounds were usually given for the two segments. The two segments were sometimes rated separately, but most often an overall pilot rating was given to the combined task. In Table C-2, these segments are shown separately with the gross acquisition tasks listed first, followed by the fine tracking tasks. Relevant details about the tasks, including the maneuver description and performance requirements, are also provided in Table C-2.

Listed together with the tasks used in previous flight research programs in Table C-2 are proposed gross acquisition evaluation maneuvers from two sources: the Standard Evaluation Maneuver Set (STEMS) developed by the Air Force and McDonnell Douglas (Ref. C-9) and the demonstration maneuvers listed in the recently-released proposed revisions to MIL-STD-1797A developed by the Air Force (Ref. C-10). Several of the maneuvers in STEMS may be classified as gross acquisition maneuvers: specifically, STEM Nos. 1, 3, 8, 10, and 11. The differences between these maneuvers are related to the maneuver scenarios and trim conditions at which the evaluations are performed. In Table C-2, some of these maneuvers have been combined based on the performance limits. For instance, STEM Nos. 3, 10, and 11 have been combined as they share the same performance limits.

All the gross acquisition maneuvers described in the literature surveyed in this study are variations of a single basic maneuver — the aggressive acquisition of a target aircraft located at a specified angular

TABLE C-2. TARGET TRACKING TASKS

Maneuver Type	Description of Maneuver	Performance Limits		Aircraft Type	Ref No.	Comments
		Desired	Adequate			
Gun tracking (gross acquis)	In trail, 200 ft; target starts 2g 180° level turn; track when 30° angle-off	Aggressively acquire within 25 mils, no overshoot	Aggressively acquire within 25 mils, 1 overshoot max.	fighter	C-11	Exposed ratcheting;combined rating for gross acquis./fine tracking
Gun tracking (gross acquis)	In trail, 1000 ft; target starts 2g level turn; track when 30° angle-off	No PIO; acquire within 10 mils, 1 overshoot max.	Acquire within 20 mils, 2 overshoots max.	fighter	C-12	Exposed ratcheting; combined rating for gross acquis./fine tracking
Gun tracking (gross acquis)	From straight and level, acquire turning target crossing canopy bow; track thru 2g turns in both directions	Stabilize within 10 mils	None given	fighter	C-13	TPS Class 79A: performed gross acquis., fine tracking (2 maneuvers) and rated separately
Gun tracking (gross acquis)	From straight and level, acquire turning target crossing canopy bow; track thru 2g turns in both directions	Within ±20 mils, no overshoot	Within ±20 mils, 1 overshoot max.	fighter	C-14	TPS Class 79B
Gun tracking (gross acquis)	In trail; target starts 2g level turn; track when 30° angle-off	Within ±25 mils, no overshoot	Within ±25 mils, 1 overshoot max.	fighter	C-15	TPS Class 80A
Gun tracking (gross acquis)	Start at 4000 ft slant range, 45° angle-off; target performs 3-4g turn into evaluation aircraft	Two sets evaluated: acquire target in 1) 6 sec, no overshoots; and 2) 7 sec, 1 overshoot max.	Acquire target in 8 sec, 2 overshoots max.	fighter	C-16	Varied desired performance; did not consider task defined well enough for inclusion in 1797A
Gun tracking (aimpoint correction)	Track target in descending (2500 fpm) constant 4g turn, adjust power to build up AOA; perform single-axis repositions of aimpoint thru turn	Aggressively acquire aimpoint within 50 mil, 1 overshoot max, for desired time (TBD)	Aggressively acquire aimpoint within 50 mil, 2 overshoots max, for adequate time (TBD)	fighter	C-9	Variation of STEM No. 1
Gun tracking (acquire/track crossing target)	Acquire target as it passes 1000 ft overhead and track in 5-6g turn	Aggressively acquire within 30 mils, 1 overshoot max., and desired time; maintain 30 mils 50% of time	Aggressively acquire within 30 mils, 2 overshoots max., and adequate time; maintain 30 mils 10% of time	fighter	C-9	STEM No. 8
Gun tracking (gross acquis)	Three maneuvers: 1) acquire target at 10-20° angle-off, 1000 ft ahead and 1000 ft above; 2) from 3000 ft behind, acquire target at TBD angle-off in descending turn; 3) acquire and track head-on target at 1.3 nm range, 5000 ft offset and 5000 ft above	Aggressively acquire within 80 mils, 1 overshoot max., and desired time	Aggressively acquire within 80 mils, 2 overshoots max., and adequate time	fighter	C-9	STEM Nos. 3, 10, and 11

TABLE C-2. TARGET TRACKING TASKS (continued)

Gun tracking (gross acquis)	Track target in S-turns at a specificed g; angle-off for start TBD	TBD time to acquire tracking solution; track within 10 mils, no overshoot	TBD time to acquire tracking solution; track within 20 mils, 2 overshoots max.	all	C-10	Proposed revision to 1797A
Gun tracking (fine)	In trail, 200 ft; target starts 2g 180° level turn; track from start of turn	No PIO; within ±5 mils 50% of time, ±25 mils rest of time	Within ±5 mils 10% of time, ±25 mils rest of time; "would fire gun"	fighter	C-11	
Gun tracking (fine)	In trail, 1000 ft; target starts 2g level turn; track from start of turn; track alternate wingtips of target	No PIO; within 2.5 mils 50% of time not to exceed 10 mils	Within 5 mils 50% of time not to exceed 10 mils	fighter	C-12	HQR correlations were good for gross acquis./fine tracking task
Gun tracking (fine)	Two tasks: 1) 2-g turns in both directions, track for at least 20 sec; 2) track in 0.2-g/sec wind-up turn to 3.5 g	±4 mils	±8 mils	fighter	C-13	TPS Class 79A: Later added unpredictable maneuvers at ends of tasks: amplified shortcomings, but did not change overall HQRs
Gun tracking (fine)	Three tasks from 1500-ft range: 1) 2-g level turns; 2) modified lazy-8 in both directions; 3) unpredictable	±5 mils 50% of time, ±20 mils rest of time	±5 mils 10% of time, ±20 mils 80% of time	fighter	C-14	TPS Class 79B
Gun tracking (fine)	Three tasks from 1500-ft range: 1) 2-g level turns; 2) modified lazy-8 in both directions; 3) unpredictable	±4 mils	±8 mils	fighter	C-15	TPS Class 80A
Gun tracking (fine)	Two tasks, in sequence after gross acquis. (above): 1) 3g, 180-270° turn; 2) 4g or 5.5g 120° turn	Two set evaluated: Track target 1) fuselage in front of horiz. stab. for 2 sec; 2) canopy for 2 sec	Track target fuselage in front of horiz. stab. for 0.5 sec	fighter	C-16	Two levels of desired performance evaluated; second preferred. Tasks are difficult, difficulty varies with range
Gun tracking (fine)	Two maneuvers: 1) track target in descending (2500 fpm) constant 4g turn, adjust power to build up AOA; 2) track at constant AOA in turn, 1500 ft range	No PIO; ±5 mils for 50% of time, ±25 mils rest of time	±5 mils for 10% of time, ±25 mils rest of time	fighter	C-9	STEM Nos. 1 and 2
Gun tracking (fine track in PA)	Track aimpoints on target at 1500 ft range, constant altitude, in gradual S-turns with straight flight segments	No PIO; ±5 mils for 50% of time, ±25 mils rest of time	±5 mils for 10% of time, ±25 mils rest of time	all	C-9	STEM No. 19
Gun tracking (fine)	Two tasks at range of 1000-2000 ft: 1) S-turns at a specified g, track minimum of 20 sec; 2) 0.2-g/sec wind-up turns	±5 mils 90% of time	±10 mils 90% of time	all	C-10	Proposed revision to 1797A

TABLE C-2. TARGET TRACKING TASKS (concluded)

Gun tracking (unpredictable traget)	Target maneuvers in g, A/S, pitch, roll, holding changes for 5-8 sec before next maneuver	No PIO; within ±5 mils 50% of time, ±25 mils rest of time	Within ±5 mils 10% of time, ±25 mils rest of time; "would fire gun"	fighter	C-11	"Demanding flying qualities task"
Gun tracking (unpredictable traget)	Target maneuvers in g, A/S, pitch, roll	No PIO; within 2.5 mils 50% of time not to exceed 10 mils	Within 5 mils 50% of time not to exceed 10 mils	fighter	C-12	
Tracking	Start behind and below target; track at 1000-1500 ft range thru defensive maneuvers; switch roles	None given	None given	fighter	C-17	More demanding than formation task
Tracking	Track thru 60° roll reversal; reversal with altitude change; pullup/pushover; reversal; random defensive maneuvering	None given	None given	fighter	C-18	
HQDT (gross acquis.)	1,500 ft range, constant-g turns with reversal approx. 20 sec apart; 0.6M, 0.7M, 0.9M	Within 25 mils with 1 overshoot max.	Within 50 mils with 2 overshoots max.	S/MTD	C-19	Evaluated all control modes
HQDT (fine)	Same as HQDT (gross)	Within ±5 mils 75% of time	Within ±10 mils 75% of time	S/MTD	C-19	Evaluated all control modes

offset from the aircraft being evaluated. In past flight research programs (Refs. C-11, C-12, C-13, C-14, and C-15), these evaluations have primarily focused on lateral maneuvering only. The STEMS include gross acquisition maneuvers in both lateral and longitudinal axes. The gross acquisition demonstration maneuvers in the proposed revision to MIL-STD-1797A are restricted to the lateral axis.

A review of the flight research experience using this task provided mixed results on its effectiveness as an evaluation task. A primary advantage is that it directly emulates an operational MTE. In addition, task aggressiveness can be varied by adjusting the starting angular offset between the target and evaluation aircraft. In general, the task has proved itself to be an adequate discriminator of different handling qualities. This cannot be stated conclusively because in several instances, the gross acquisition and fine tracking tasks were only given one overall pilot rating. It is possible, in these cases, that one segment of the task (either the gross acquisition or the fine tracking) was weighted more in the ratings. Detailed inspection of the pilot comments from these experiments is required before any conclusions are drawn from these results.

In one flight research program (Ref. C-11), the large amplitude maneuvering required for the task exposed a high-frequency PIO-like phenomenon caused by the interaction of the pilot arm dynamics and the stick characteristics (roll ratchet). This phenomenon had been experienced previously in the F-16 fighter.

The available literature on this task also point out several shortcomings. These are listed below.

- Task is difficult to constrain
- Task is time-consuming in a flight environment
- Performance is hard to judge

The first of these is probably the most important. The task depends on another target aircraft and it is difficult to repeatedly reproduce (with reasonable accuracy) all the required task parameters such as range and angle-off. Usually, several repeat evaluations are necessary with any task before pilot ratings are obtained. There is, therefore, a need for the task to be repeatable.

Another disadvantage is that performance is difficult to judge. In all the flight research evaluations, a fixed gunsight reticle on the HUD was used for aiming and judging performance. Problems that have been noted include difficulties due to pendulum effects and those encountered in sighting an aim point on the target aircraft. In all the evaluations surveyed for this study, the aim point on the target aircraft was some physical feature on the aircraft that, under certain circumstances including long ranges, was difficult to discern. Most often the aim point was the tail pipe or the junction between the tail pipes.

The Ref. C-16 research program evaluated the gross and fine tracking tasks and concluded that they were not suitable for inclusion in MIL-STD-1797 without further refinement.

b. Non-Precision Aerobatics Maneuvers

Several of the MTEs in Category D can be described as non-precision aerobatics maneuvers. Maneuvers such as the barrel roll and Split-S evaluate the aircraft through a wide range of load factors and angles of attack. They also emphasize both large- and small-amplitude capture of attitudes, load factors, and angles of attack. The aerobatics maneuvers listed under Category D in Table C-1 are, therefore, suitable candidate demonstration maneuvers. A significant amount of research is necessary, however, to determine desired and adequate performance boundaries for these tasks.

Combat maneuvers such as the high and low speed yo-yo are also suitable candidates for demonstration maneuvers as they represent basic air combat maneuvers. More research is needed here also to determine performance limits.

There is only anecdotal evidence of the use of aerobatics maneuvers in early flight test programs (see Ref. C-36). These were not formal evaluations and, as stated in Ref. C-36, were usually unauthorized! A high speed yo-yo maneuver was used in the flight test program of Ref. C-37 to reposition the aircraft during air-to-air tracking evaluations. No set procedure or performance limits were prescribed.

c. HUD Tracking

Another alternative that may be used as a demonstration maneuver for large-amplitude maneuvering is the HUD tracking task. The HUD tracking task has no direct relationship to the MTEs in this category but it can emulate the essential characteristics of the tasks and thereby serve as a surrogate. The attractiveness of the HUD tracking task is that it is a well-defined task that is repeatable with clearly defined and easy-to-judge performance limits.

The HUD tracking task has recently found acceptance as a good handling qualities evaluation task for small-amplitude tracking. A compilation of the HUD tracking tasks used in flight research programs is presented in Table C-3. In this task, the error between the aircraft state and an input signal is presented to the pilot on the HUD. The pilot then attempts to null the error, and by doing so, attempts to track the input signal.

For evaluating the handling qualities in the large-amplitude maneuvering required by these MTEs, the input signal to the tracking task can be of very low bandwidth and large amplitude. The input signal is deterministic (usually a sum-of-sines or a step/ramp-type of discrete series) and may be tailored to the capabilities of the aircraft and task requirements.

TABLE C-3. HUD TRACKING TASKS

Input Type	Axis	Input Bandwidth	Input Duration (max)	Performance Limits		Aircraft Type	Config-uration	Ref No.	Comments
				Desired	Adequate				
Discrete (step/ramp)	pitch & roll	2-3 inputs/ 20 sec	≈90 sec	No PIO ±5 mils 50% of time	±10 mils 50% of time	fighter	up-and-away	C-12	Not discriminating; emphasizes pitch
Discrete (step/ramp)	roll	≈4 inputs/ 20 sec	≈90 sec	No PIO ±5 mils 50% of time	±10 mils 50% of time	fighter	up-and-away	C-12	HQRs show better correlation
Discrete (step/ramp, continuous)	roll	≈4 inputs/ 20 sec	≈2 min	No PIO ±2° 90% of time	±2° 50% of time	fighter	up-and-away, landing	C-11	max 60° inputs up-and-away; max 30° inputs landing
Discrete (step/ramp, continuous)	heading	1-2 inputs/ 20 sec	≈2 min	±1° 75% of time ±3° rest of time	±1° 25% of time ±5° rest of time	fighter	up-and-away, landing	C-11	max 30° inputs up-and-away; max 15° inputs landing; not discriminating, eliminated
Discrete (steps)	pitch	3-5 inputs/ 20 sec	≈100 sec	[See Comments]	[See Comments]	fighter	landing	C-20	No specific performance limits ("minimize error")
Discrete (steps)	pitch	3-5 inputs/ 20 sec	≈100 sec	[See Comments]	[See Comments]	fighter	up-and-away	C-21	No specific performance limits ("minimize error")
Discrete (steps)	roll	1-3 inputs/ 20 sec	≈90 sec			fighter	up-and-away	C-22	Task displayed on ADI
Discrete (step/ramp)	pitch (&roll?)		90 sec			transport		C-23	Task displayed on ADI
SOS	roll	0.55 rad/sec	≈90 sec	No PIO ±5 mils 50% of time	±10 mils 50% of time	fighter	up-and-away	C-12	Not discriminating
SOS	roll	1.5 rad/sec	≈90 sec	No PIO ±5 mils 50% of time	±10 mils 50% of time	fighter	up-and-away	C-12	HQRs show better correlation
SOS	pitch	1.44 rad/sec "cutoff"				transport		C-23	Task displayed on ADI
Filtered noise	pitch			[See Comments]	[See Comments]	fighter	up-and-away	C-21	No specific performance limits ("minimize error")

The HUD tracking task may be used for attitude tracking, flightpath tracking, or any combination of these. With different input characteristics, this task may be considered a surrogate to most of the MTEs in Category D; i.e., it will reproduce the salient maneuver features in the MTEs. The HUD tracking task may not be appropriate for evaluations involving airspeed. Airspeed captures are, in any event, not a significant factor in any of the MTEs in Table C-1.

The primary attractiveness of the HUD tracking task as a demonstration maneuver is that it is self-contained and does not require a target aircraft. Further, the deterministic nature of the input signal allows the maneuver to be standardized and tailored to different aircraft classes. Development of the HUD tracking task as a demonstration maneuver for Category D tasks will require further research to define suitable disturbance signals, displays, and performance limits.

4. Non-Aggressive, Precision Up-and-Away MTEs (Category C)

The MTEs from Table C-1 that fall within this category are listed below:

- Aerial recovery
- In-flight refueling — receiver
- Close formation

These MTEs emphasize small-amplitude maneuvers. All the maneuvers are precise in nature and, therefore, emphasize closed-loop control. In-flight refueling and close formation flying are essentially stationkeeping tasks while aerial recovery may be classified as a flightpath control task. Aircraft states that are closely controlled are attitude and airspeed. Due to the small and precise nature of the required flightpath control in any of these MTEs, tight control of attitude as an inner loop for outer-loop flightpath control is essential. The primary aircraft response characteristics that will influence the achievable performance in these tasks will be the short-term pitch and roll characteristics as determined by the short-period and roll subsidence modes, and the flightpath-to-pitch attitude lag T_{θ_2}.

For most operations, these MTEs may be classified as non-aggressive because there are no real time constraints or urgency related to the performance of these tasks. Nonetheless, the aggressiveness of these tasks may be altered by changing several parameters related to the task. For instance, an increase in turbulence intensity or a requirement to perform the maneuver to more stringent performance standards might increase the workload and urgency related to a task to a level where it would be better classified as an aggressive, precise, MTE. In the development of any demonstration maneuvers for these MTEs, therefore, the performance limits must be carefully determined to ensure that the resulting level of aggressiveness that is elicited from the task is not unrealistic.

Formation flying and air-refueling tasks have been used in a number of flight research and flight test programs. In most flight test programs the evaluations have been qualitative and were designed to qualify the aircraft to perform these MTEs, not specifically for handling qualities assessment. Use of these maneuvers by the flight research community has been relatively sparse. Details of these tasks as used by the flight research community are compiled in Tables C-4 and C-5 for formation flight and air refueling, respectively.

Experience with the use of the formation flying task for handling qualities evaluation has been largely unsatisfactory, as documented in the majority of the literature surveyed in this study (see Table C-4). The task was generally not found to be a good discriminator of aircraft handling qualities and, in several instances, it was discontinued as an evaluation task mid-way through the experiment. The primary problem was that the task was generally considered too easy due to the aircraft separation requirements mandated by safety constraints. In addition, task performance was usually difficult to judge.

Experience with the use of the air refueling task (as receiver) has been more positive, though not conclusive (see Table C-5). Both probe-and-drogue and boom refueling tasks have been used, although a majority of the evaluations have been with the probe-and-drogue system. In a flight research program using the Air Force NT-33 variable stability aircraft (Ref. C-11), the air refueling task (using a probe-and-drogue system) was thought to be a demanding flying qualities task. In a more recent experiment by the TPS using the same aircraft and the same refueling system (Ref. C-26), however, the task was considered too easy. The difference between these two tasks may be the performance constraints. In the Ref. C-11 experiment, the requirement was for a successful hookup with a further requirement to maintain position within specified limits. In the Ref. C-26 experiment, the requirement was simply to complete a prescribed amount of successful hookups within a prescribed number of attempts. These performance limits have also been adopted for the demonstration maneuver for probe-and-drogue air-refueling in the proposed revision to MIL-STD-1797A.

The performance constraints adopted in the TPS experiment (Ref. C-26) are certainly compatible with the task being evaluated; they may be too lenient, however, when the level of turbulence is low, and the task may not be very discriminating. This very possibly was the reason that the task was assessed as being too easy. It may be necessary, therefore, to include some position keeping requirements in addition to the requirement for hookup in order to maintain the task workload at an adequate level when external disturbances are negligible. The difficulty, in this case, is judging performance.

In refueling tasks with a boom-type system, the task is to track the boom within specified performance constraints. Performance is assessed through an aiming reticle on the HUD which makes it easier to judge

TABLE C-4. FORMATION FLYING TASKS

Maneuver Type	Description of Maneuver	Performance Limits		Aircraft Type	Ref No.	Comments
		Desired	Adequate			
Maneuvering target	Target's 5 or 7 o'clock, 50 ft spacing (closer if possible); target straight-&-level, then 30° bank 180° right turn, 60° bank 180° left turn	No PIO; within ± 3 ft 90% of time, ± 10 ft rest of time	Within ± 5 ft 50% of time, ± 10 ft rest of time	fighter	C-11	"Obvious that this task was not the critical flying qualities determinant." Eliminated from program
Maneuvering target	Target's 5 or 7 o'clock, 50 ft spacing (closer if possible); target straight-&-level, then 30° bank 180° right turn, 60° bank 180° left turn	No PIO; within ± 2 ft vertically and horizontally	Within ± 4 ft vertically and horizontally	fighter	C-12	Task too easy "likely due to... separation requirements for safe flight test." Also time consuming; eliminated
Simulated air refueling	25-50 ft below target, between 10 and 100 ft horizontally; use "abrupt pitch inputs" to position 10 ft below target	None given	None given	shuttle (low L/D)	C-24	Used as surrogate for landing with very high time delays;"Not as demanding as actual landings"
Close trail formation	Start 250 ft behind, 100 ft below target; maneuver to 8-10 ft behind and below target	No limits stated; "Obscure target's A/B nozzle with canopy bow"	No limits stated	shuttle (low L/D)	C-25	Not well-defined task; "Not entirely representative of normal piloting tasks"
Formation	Join target in loose formation; tighten position as much as possible; drop back	None given	None given	fighter	C-17	

TABLE C-5. AIR REFUELING TASKS

Maneuver Type	Description of Maneuver	Performance Limits		Aircraft Type	Ref No.	Comments
		Desired	Adequate			
Probe and drogue	Pre-contact 50-ft trail, 20 ft laterally; attempt 3 contacts of 30, 15, and 15 sec	No PIO; Contact on first attempt, position within ±3 ft	Contact after multiple attempts; position within ±5 ft	fighter	C-11	Considered task to be "equally demanding [as gun tracking] flying qualities task"
Probe and drogue	Standard refueling procedure with KA-3 tanker; number of hook-ups, etc., not specificed	None given	None given	fighter	C-18	Ratings generally better for refueling than for target tracking with same configurations
Probe and drogue	3-5 kt closure rate until hook-up; disengage and repeat; attempt 3 hook-ups	Complete 3 hook-ups in no more than 6 attempts (50%); max. PIO rating of 2	Complete 3 hook-ups in no more than 12 attempts (25%); max. PIO rating of 4	fighter	C-26	"Considered to be too easy by the project pilots. No more than six attempts were ever required to achieve three hook-ups;" HQRs varied from 1 to 9
Probe and drogue	3-5 kt closure rate until hook up; hold for 30 sec; disengage and repeat	Complete at least 50% of attempted hook-ups	Complete at least 25% of attempted hook-ups	all	C-10	Proposed revision to 1797A
Tanker boom	From straight and level flight, track boom for 2-4 min; boom is stationary or slowly moving (less than 1 deg/sec)	±5 mils for 90% of the time	±10 mils for 90% of the time	all	C-10	Proposed revision to 1797A; alternate task description: align boom with a feature on tanker fuselage and track for 2-4 min; performance limits based on tanker
Tanker boom	From straight and level flight, track boom 10-50 ft behind with pipper on precise position on boom; change aimpoints on boom; use end of boom if boom is slowly moving	No objectionable PIO; maintain aimpoint within 30 mil for 50% of task	Maintain aimpoint within 50 mil reticle for 50% of task	all	C-9	Found longitudinal position control to be dominating in simulation; may require copilot to control airspeed
Tanker boom	From pre-contact 50-ft trail, 30-deg depression angle; align boom nozzle with yellow centerline on tanker. Start clock once aligned	±10 ft fore/aft, ±8 deg up/down, ±3 deg azimuth;boom lined up with 4-ft-wide zone along centerline; hold for total of 60 sec	±10 ft fore/aft, ±8 deg up/down, ±8 deg azimuth; boom lined up within width of tanker fuselage; hold for 2 min	transport	C-40	Adequate performance is related to operational requirements (fuel transfer time and boom envelope)

performance. For larger (Class III) aircraft, where HUDs with aiming reticles are generally not available, features on the tanker fuselage and boom may be used to judge performance. An example of the use of such performance criteria in an air refueling task is presented in Ref. C-40.

Reference C-40 describes a flight test program that was specifically directed towards developing handling qualities evaluation tasks for Class III aircraft. This study is particularly interesting since it provides a source of data on the operational use of evaluation maneuvers using fleet aircraft. One of the tasks developed in this program was an air refueling task. The evaluations used a KC-135R tanker aircraft and three different receiver aircraft (C-18B, KC-135A, and C-141A). Task performance was judged primarily by using distinctive features on the lower fuselage (belly) of the tanker with some feedback from the boom operator on the relative positioning of the receiver. The evaluation pilot was required to line up the boom with a painted centerline stripe on the belly of the tanker and keep it within a 4-ft-wide zone for desired performance and within the complete width of the tanker fuselage for adequate performance. The study found that the task was repeatable, measurable, and representative of operational maneuvering but noted that the task details including performance criteria were unique to the KC-135R tanker.

Wherever possible, performance requirements in handling qualities evaluation tasks must be related to actual operational requirements. In the Ref. C-40 study, the adequate performance criteria were based on operational requirements for Class III aircraft. For instance, the stationkeeping criteria (fore/aft, up/down, and azimuth, see Table C-5) reflect the allowable boom envelope and the time requirement of 2 min represents the time required to transfer minimum landing pattern fuel for a Class III aircraft.

Both the close formation and air refueling tasks emphasize stationkeeping relative to another aircraft in level and maneuvering flight. A single demonstration maneuver may suffice, therefore, to evaluate the handling qualities of an aircraft in these tasks. The ineffectiveness of the close formation task indicates that it should be further refined or eliminated. This leaves the air refueling task as the most promising candidate for a demonstration maneuver in this category.

5. Non-Aggressive, Precision Terminal MTEs in Good Visibility (Category C)

The MTEs that fall into this category in Table C-1 are:

- Low Altitude Parachute Extraction (LAPES)
- Catapult takeoff
- Approach
- Precision landing
- Tactical final approach

These MTEs emphasize precise control of flightpath and speed. As with the up-and-away tasks in this category, these tasks emphasize closed-loop piloted control. Good handling qualities are, therefore, important if the desired task performance is to be met with a reasonable amount of pilot workload in these flight phases. As with the previously discussed terminal area MTEs, these MTEs will also be divided attention tasks. It is possible that the precision required by these tasks may preclude any significant divided attention operation even with an aircraft that exhibits good handling qualities. The primary aircraft response characteristics that will impact task performance for these tasks are the lateral and longitudinal dynamic modes in attitude and flightpath that determine the short-term response.

A good example of a precision terminal MTE is the offset landing task. This task has been widely used in flight research activities and is, by a fair margin, the most popular handling qualities evaluation maneuver. A compilation of the precision offset landing tasks used in past flight research activities is presented in Table C-6. In all but one experiment, the task involved a lateral offset only. The initial conditions for this task are usually on-glideslope with a lateral offset. At a specified altitude, the evaluation pilot corrects the lateral offset and attempts to land the aircraft within a specified touchdown region on the runway. The purpose of the lateral offset is to perturb the aircraft during the final stages of the approach and force the pilot into a tight closed-loop control strategy.

This task has, in the past, proved to be a good discriminator of aircraft handling qualities. To a large extent, this is due to the well-constrained nature of the task and clearly defined and observable performance limits. As shown in Table C-6, this task has most often been used to evaluate conventional aircraft configurations (both fighters and transports), operating on a nominal 3-deg glideslope. The desired and adequate performance boundaries are similar for most of these experiments with the notable exception of those used in the F-15 S/MTD simulation evaluations (Ref. C-41). The evaluation task in the Ref. C-41 simulation was terminated prior to touchdown but the intended touchdown zone was a 20-ft by 60-ft area on a bomb-damaged runway. These boundaries are also suggested for the STEMS offset landing task (Ref. C-9). Reference C-9 also recommends, however, that the criteria be refined based on aircraft type and precision required. The S/MTD was designed for the special purpose of landing on bomb-damaged runways and it will not be appropriate to apply these performance requirements to any other type of aircraft.

This task has also been used to evaluate the handling qualities of a powered-lift STOL aircraft operating on a 6-deg glideslope (Ref. C-32). Since STOL operations generally require precise landings, the offset landing task used in the Ref. C-32 study was more challenging and involved both lateral and

TABLE C-6. LATERAL OFFSET APPROACH AND LANDING TASK

Lateral Offset	Point of Offset Correction	Trim Speed Desired	Trim Speed Adequate	Trim Glideslope	Sink Rate Desired	Sink Rate Adequate	Touch Down Area Desired	Touch Down Area Adequate	Disturbance	Aircraft Type	Ref No.
200 ft left or right	180 ft AGL	132 ±3 KIAS	132 ±5 KIAS	3°	0-3 fps	3-6 fps	±10 ft x ±500 ft	±20 ft x ±1000 ft	(1 -cos) alpha gust	transport	C-27
150 ft	200 ft AGL	135 KIAS nominal		3°			±5 ft x ±250 ft	±5 ft x ±500 ft		fighter	C-11
undefined offset				3°	nominal		50 0 ft long zone			fighter	C-20
300 ft left or right	150-200 ft above ground	trim ±5 kts 125-133 KIAS	trim -5/+10 kts 125-133 KIAS	2.5° and 3°			±5 ft x ±250 ft	±25 ft x -250/+750 ft		fighter	C-12
150 ft left or right	beginning of runway overrun	trim ±5 kts	trim -5/+10 kts	2.5°			±5 ft x ±250 ft	±25 ft x ±500 ft		fighter	C-28
150 ft left or right	100 ft above ground	trim ±5 kts	trim -5/+10 kts	2.5°			±5 ft x ±250 ft	±25 ft x ±500 ft		fighter	C-29
150 ft	100 ft above ground	190 KIAS at touchdown		1°						shuttle (Low L/D)	C-24
850 ft right	200 ft AGL						20 ft x 60 ft	50 ft x 100 ft		fighter	C-9
150 ft right	150 ft above ground	trim ±5 kts	trim ±10 kts	2.5°			50 ft x 400 ft	100 ft x 1000 ft		fighter	C-16
250 ft	200 ft above ground			3°					blend of natural and artificial	transport	C-30
300 ft left or right	200 ft above ground	trim ±3 kts	trim ±5 kts	2.5°	0-4 fps	4-7 fps	±10 ft x 500 ft	±27 ft x 1500 ft	(1 -cos) vertical gust	transport	C-31
50 ft or 100 ft left or right	100 ft above ground			6.0°	0-5 fps	0-12 fps	100 ft x 200 ft		natural turbulence	STOL (QSRA)	C-32
200 ft	200 ft above ground									transport (C-5A)	C-33
200 ft or less	150 ft above ground	trim ±5 kts	trim ±10 kts		80% of gear limit	less than gear limit	50 ft x 500 ft	100 ft x 1000 ft		conventional	C-10
200 ft or less	150 ft above ground	landing speed ±3 kts	landing speed ±5 kts		50% of gear limit	less than gear limit	20 ft x 100 ft	50 ft x 500 ft		STOL & carrier land	C-10
300 ft (1 dot at 200 ft AGL)	200 ft AGL	approach speed ±5 kts		ILS glideslope 3° or 2.5°	no bounce; no hard landing	6.7 fps	±20 ft x ±200 ft	±40 ft x ±500 ft	natural turbulence	transport (C-135, C-18, C-141)	C-40

longitudinal offsets from the localizer and glideslope, respectively. The touchdown constraints were also more stringent.

The flight test experiment reported in Ref. C-40 evaluated the offset landing as a handling qualities evaluation task for Class III aircraft. The basic task details were similar to those for the other studies listed in Table C-6. Three different Class III aircraft in the Air Force inventory were evaluated. The study found that the task was repeatable, measurable, and representative of operational maneuvering. It was effective in actively exciting the aircraft in all axes of control.

The Ref. C-40 study represents a valuable source of data on the practical issues related to the use of demonstration maneuvers. The adequate performance criteria in the Ref. C-40 flight tests were based on operational requirements. The adequate landing zone represented a requirement to land within the first third of the runway available (based on a minimum runway length of 6000 ft) and the maximum allowable lateral displacement for a Class III type aircraft on a 150 ft wide runway. Adequate and desired touchdown sink rates were initially prescribed in the study (based on structural loading for the test aircraft) but were modified to more generic requirements (no bounce and no hard landing) because of the difficulty in measuring touchdown sink rate. For safety reasons, evaluations were not performed in crosswinds greater than 10 kts and bank angles of greater than 5 deg were not permitted at altitudes below 50 ft above ground.

A lateral offset landing task is also specified in the proposed revisions to MIL-STD-1797A (Ref. C-10). The proposed revision includes different performance limits for conventional and STOL landings (including more stringent requirements on airspeed control for STOL aircraft). The offset landing task in Ref. C-10 is similar to those that have been used before in flight research studies. The established history of its utility as a handling qualities evaluation task makes it a strong candidate as a demonstration maneuver.

There are a few additions to the offset landing maneuver that are worth considering. First, the basic lateral offset may be complemented by longitudinal offsets to further increase the realism of the task and force closed-loop pilot operation. Such dual offsets were used in the Ref. C-32 evaluations. Second, possible ways of including the effect of ambient conditions (specifically crosswinds and windshears) should be investigated. The crosswind landing is a good example of a closed-loop precision task and the inclusion of this as a variation to the offset landing task might be appropriate. Finally, the task and its performance constraints must be further verified to ensure that they are compatible with all classes of aircraft and control techniques (backside versus frontside control). Aircraft size should be factored into

the task description, for example, to allow aircraft with large wing spans to perform the offset correction at higher altitudes.

The offset landing task may be extended to create a new demonstration maneuver that is representative of the LAPES MTE. The LAPES MTE is not the same as a precision landing, however, and the landing task must be heavily modified if an aircraft is to be properly evaluated for LAPES. The primary difference is that the airplane must not land in LAPES, but must instead have sink rate arrested at very low altitude. Periodic pitch disturbances, similar to the effects of cargo dropping from the rear of the aircraft, must also be devised. There is no test data that can be used to establish any performance guidelines for this task. It is possible that the Air Force's experience with evaluating the C-17 transport for this maneuver will provide some insights.

6. Non-Aggressive, Precision Terminal MTEs in Degraded visibility (Category C)

These MTEs are not specifically cited in Table C-1. They are simply the terminal MTEs listed above but with special emphasis on operations in degraded visual environments. Examples of degraded visual environments include low visibility due to weather or flight using vision aids such as Forward Looking Infra-Red (Flir) and night vision goggles (NVGs).

These MTEs will emphasize closed-loop activity with more compensatory control on the part of the pilot. This is due to the degradation in the pilot's ability to predict flightpath in the degraded visual environment. With insufficient visibility to predict the flightpath into the near future, the pilot must rely more on a compensatory control strategy.

There is no existing database for evaluation maneuvers in a degraded visual environment. It is likely that the performance limits outlined in the 1797 revision (Ref. C-10) will be too stringent and the task itself will be unsafe for use in a degraded visual environment without some modification.

7. Aggressive, Precision MTEs (Category A)

The MTEs that are included in this category in Table C-1 are:

- Tracking a maneuvering target
- Ground attack
- Weapon delivery and launch
- Terrain following
- "Herbst" turn
- Precision aerobatics

These MTEs primarily emphasize small-amplitude attitude control. Larger amplitude flightpath control will also be required in MTEs such as terrain following and precision aerobatics. The precision required in the tracking MTEs necessitates aggressive, closed-loop pilot behavior. The primary aircraft response characteristics that will influence handling qualities assessments in these tasks will be the short-term response dynamics due to the effective short-period and roll subsidence modes.

Since tracking tasks, by definition, require closed-loop pilot operation, they have been used extensively in flying qualities research programs. There are three basic variants of the tracking task that have been used in past research (and some flight test) programs. These are:

1) Tracking a maneuvering or fixed target (air-to-air or air-to ground)
2) The Handling Qualities During Tracking (HQDT) task
3) HUD tracking tasks

Of the different types of tracking tasks, the air-to-air fine tracking task is the one that has been used the most in flying qualities evaluations. A compilation of these is presented in Table C-2. Included in this Table are the fine tracking tasks specified in STEMS (Ref. C-9) and the proposed revision to MIL-STD-1797 (Ref. C-10).

Many variants of the fine tracking task have been evaluated in past research programs. The variations involve the maneuvers performed by the target aircraft (see Table C-2). The basic task has been identified, through extensive experience with its use, as a demanding flying qualities task. It is, however, subject to the same shortcomings that were identified for the gross acquisition task. The primary shortcomings are the difficulties in constraining the task and in judging performance. A primary difficulty is the variation in task aggressiveness and, hence, performance, with range to the target. A flight test study by the USAF TPS (Ref. C-16) specifically investigated this task and concluded that it needed further refinement before inclusion in the specification. Several recommendations are made in Ref. C-16 that would remedy some of the problems associated with this task. These should be taken into consideration in the development of an air-to-air fine tracking task as a demonstration maneuver.

Instances where the air-to-ground fine tracking task has been used as an evaluation maneuver in previous flight research efforts are documented in Table C-7. An adaptable target lighting array system (ATLAS) has been developed at NASA to aid in assessing ground attack handling qualities. This system is a suitable candidate for a ground attack demonstration maneuver. This task is difficult to constrain or repeat. Primarily, task difficulty is a function of range as in the air-to-air tracking task. Therefore, it

TABLE C-7. AIR-TO-GROUND TRACKING TASKS

Maneuver Type	Description of Maneuver	Performance Limits		Aircraft Type	Ref. No.	Comments
		Desired	Adequate			
Simulated dive bombing	Single bomb release at predefined point; dive from 12,000 ft to 5,000 ft	None given	None given	fighter	C-18	Simulated forward c.g. shift corresponding to bomb release
Simulated dive bombing	From 225 KIAS at 12000 ft msl, dive at a 50° angle; release at 3000 ft agl and 325 KIAS, 4g pullout with wings level and 1500 ft recovery minimum	None given	None given	fighter	C-34	TPS Class July 77 (Appendix B of Ref. 26); insufficient data obtained for this task
Ground attack	Pullup, wingover, track, pullup; track a preselected ground target	None given	None given	fighter	C-22	High load-factor maneuvering
Ground attack	Pullup, wingover, track, pullup	None given	None given	fighter	C-21	
Ground tracking (ATLAS)	In a shallow (15°) dive, acquire a series of ground targets that light in random patterns	None given	None given	fighter	C-35	
Ground tracking (gross acquis)	Aggressively acquire a sequence of widely-spaced ground targets	Acquire within 10 mils, 1 overshoot max., time limit TBD	Acquire within 20 mils, 2 overshoots max., time limit TBD	fighter	C-10	Proposed revision to 1797A; evaluates ability to switch targets
Ground tracking (fine)	Continuously track sequence of ground targets for a specified time	Acquire within 5 mils 90% of tracking time	Acquire within 10 mils 90% of tracking time	fighter	C-10	Proposed revision to 1797A; evaluates ability to track single targets

might be advisable to set aside the use of this task as a demonstration maneuver until these problems are resolved.

The HQDT task has been used mainly in flight test programs (Refs. C-38 and C-39, for example). Although it has been used for flying qualities assessment, it is not presently designed for this purpose since performance limits are not specified. The requirement is for the pilot to "track as tightly as possible." The assessment of handling qualities is, therefore, purely qualitative. Without clearly defined performance limits, HQDT is not a suitable demonstration maneuver for these MTEs.

The HUD tracking task has been used, in past flight research programs, as a surrogate to the air-combat fine tracking tasks. Table C-3 lists the use of this task as documented in the literature. The HUD tracking task is also listed in the proposed revision to MIL-STD-1797A as a suitable surrogate for the air combat evaluation maneuvers. Experience with this task has proved it to be well-constrained and repeatable and a good discriminator of vehicle handling qualities. Since it does not require a target aircraft, the HUD tracking task can be flown in any flight condition, anywhere, at any time.

Development of the HUD tracking task as a demonstration maneuver will require further research to determine the nature of the input signal, display, and performance limits. The input type (sum-of-sines or discrete) and bandwidth should be tailored to the capabilities of the aircraft class and the control technique being used (frontside or backside).

C. CANDIDATE DEMONSTRATION MANEUVERS

1. Summary of MTEs and Demonstration Maneuvers

Table C-8 summarizes all of the Mission-Task-Elements proposed in Table C-1 and indicates possible corresponding demonstration maneuvers for each MTE. Since most of these MTEs apply only to certain aircraft Classes, the applicable Classes are also listed. These Class definitions are unchanged from those of MIL-STD-1797A; for example, it is assumed that Class IV includes trainers for Class IV aircraft as well.

As Section B clearly indicated, the potential demonstration maneuvers have varying levels of maturity, from well-established tasks such as offset landing to entirely new tasks (for handling-qualities evaluation purposes, at least) such as the high and low yo-yos. An estimate of the level of maturity for each maneuver, as well as its value as a demonstration maneuver, is indicated in Table C-8. All demonstration maneuvers are indicated as existing, requiring refinement, or proposed. These designations are not meant to be conclusive; for example, some refinement may be justified for all of the maneuvers as they are

TABLE C-8. DEMONSTRATION MANEUVERS FOR MISSION-ORIENTED FLYING QUALITIES

MTE Category	Mission-Task-Element	Demo Maneuver	Applicable Aircraft Class(es)	Status of Maneuver: Proposed (new)	Existing	Requires refinement
Non-precision, non-aggressive MTEs (new Category B)	Reconnaisance (RC)	Straight & level flight; cruise maneuvering	all	✓		
	In-flight refueling – tanker (RT)	Straight & level flight; cruise maneuvering	II, III	✓		
	VMC and IMC loiter/cruise/climb/descent (LO, CR, CL, D, ED, DE)	Straight & level flight; cruise maneuvering	all	✓		
	Normal takeoff (TO)	Takeoff	all	✓		
	Waveoff/go-around (WO)	Go-around	all	*		
	Non-precision landing (L)	Offset landing	all		*	
Non-precision, aggressive MTEs (new Category D)	Gross acquisition using loaded roll	Air-to-air tracking (gross acquisition); high-AOA lateral and longitudinal gross acquisitions	IV		✓	
	Missile defense with loaded roll	Pitch and roll attitude captures; high-AOA roll and capture	IV			✓
	Anti-submarine search and maneuvering (AS)	Straight & level flight; cruise maneuvering	II,III,IV		*	
	High-speed max g turn	High-speed turn	IV	*		
	"Herbst" turn	"Herbst" turn	IV	*		
	Split S, chandelle, non-precision aerobatics	Pitch and roll attitude captures	I, IV			✓
	High yo-yo	High yo-yo	IV	✓		
	Low yo-yo	Low yo-yo	IV	✓		
Precision, non-aggressive MTEs (new Category C)	Aerial recovery (AR)	Flightpath captures	II, III	✓		
	In-flight refueling – receiver (RR)	Probe-and-drogue refueling	I,II,IV			✓
		Tanker boom tracking	all			✓
	Low-altitude parachute extraction (LAPES)	Precision low-altitude flight	II, III	✓		
	Catapult takeoff (CT)	Precision takeoff	IV	✓		
	Approach (PA)	Precision ILS tracking	all			✓
	Precision landing	Precision offset landing	all			✓
	Close formation (FF)	Close formation	all		*	
	Tactical final approach	Heading & altitude captures	III, IV	✓		
Precision, aggressive MTEs (new Category A)	Tracking maneuvering target (CO)	Air-to-air (fine tracking)	IV		✓	
		HUD tracking	IV	✓		
	Ground attack (GA)	Air-to-ground tracking	II, IV		*	
	Weapon delivery and launch (WD)	HUD tracking	IV	✓		
		Air-to-air (fine tracking)	IV		✓	
	Terrain following	Simulated g-capture (HUD tracking)	IV	✓		
	Precision aerobatics	Pitch and roll attitude and g captures	I, IV			✓

* These maneuvers have not proven, or are not considered, to be discriminating of flying qualities. It may be appropriate to investigate surrogate demonstration maneuvers for these MTEs.

adapted for different aircraft Classes. Those that are proposed new maneuvers may require only minimal flight investigation to define all of the task details and performance limits.

Maneuvers in Table C-8 judged to not be discerning of differences in flying qualities are marked by an asterisk (*) in one of the status columns. This is not to suggest that the MTE is unimportant, but only that an appropriate demonstration maneuver has not yet been identified for that MTE. As an example, the best demonstration maneuver for the catapult takeoff MTE is a catapult takeoff. The intent here, however, is to define some maneuver that evaluates the flying qualities of the airplane as required for the catapult takeoff, without requiring an actual catapult facility.

2. Example Demonstration Maneuver Descriptions

Complete descriptions of three candidate demonstration maneuvers are provided below to illustrate the format and detail necessary to ensure that each maneuver is clearly defined in terms of intended aircraft Class, control technique, and operating environment. Two of the maneuvers are precision offset landing maneuvers with variations in task definition and performance limits as appropriate for the operating visual environment. The precision offset landing maneuver is currently the most mature demonstration maneuver with proven performance limits and procedures for VMC operations. The requirements for VMC operation, stated below, are composites of those used in previous flight tests (see Table C-6). Requirements for IMC/degraded visual environment operations are not well defined and have not been tested in flight. Tentative requirements are presented below for this maneuver based on the relatively greater degree of difficulty expected for operations in a degraded visual environment where visual information may only be available from a display of the outside visual scene with a limited field-of-view (such as night vision goggles or forward-looking infra-red).

The third candidate maneuver presented below is for a STEMS maneuver (Air-to-Air Tracking, STEM 2). The basic task and performance limits are identical to those provided in Ref. C-9 but the maneuver has been transcribed into the proposed standard format.

Precision offset landing (VMC)

a. Objectives.

- Check ability to precisely control horizontal and vertical flightpath and airspeed.
- Check ability to precisely control sink rate and attitude in the flare.
- Check tendency for nose bobble or PIO.
- Check control sensitivity and harmony in landing.

b. Description of maneuver. Initiate the maneuver approximately a mile out on final approach with a lateral offset of at least 200 ft from the runway centerline and a vertical offset above

the normal approach angle of at least 200 ft with the gear and flaps up. At the start of the maneuver, lower flaps and gear and capture the glideslope while maintaining the lateral offset. The approach angle (glideslope) shall be as appropriate for the aircraft being tested (roughly 3-deg for conventional approach or steeper for a STOL approach). At 200 ft AGL aggressively correct the lateral offset to land on the runway centerline with wings level. Touchdown within the prescribed touchdown zone with the aircraft centerline within the width of the zone and the main gear within the length of the zone. The task may be performed in any wind or turbulence conditions as allowed by the operational limits of the aircraft. Testing in extreme wind conditions (crosswinds and shears) is recommended. Additional constraints that are necessary for safety may be implemented as appropriate. For example, with Class III aircraft, restrictions may be placed on bank angles at low altitude.

c. Desired performance.

1. Conventional approach and landing.

- Maintain approach angle within ±1 deg (±1/2 dot ILS).
- Maintain approach airspeed within ±5 kts.
- Touchdown zone:
  - 10 ft wide by 400 ft long (Class I and IV aircraft).
  - 20 ft wide by 400 ft long (Class II and III aircraft).
- Touchdown sink rate less than 80% of the gear limit (or no bounce and no hard landing if touchdown sink rate is difficult to measure).
- No tendency for pitch bobble or PIO.

2. STOL approach and landing.

- Maintain approach angle within ±1 deg (or ±1/2 dot ILS).
- Maintain approach airspeed within ±3 kts.
- Touchdown zone:
  - 10 ft wide by 60 ft long (Class I and IV aircraft).
  - 20 ft wide by 100 ft long (Class II and III aircraft).
- Touchdown sink rate less than 50% of the gear limit (or no bounce and no hard landing if touchdown sink rate is difficult to measure).
- No tendency for pitch bobble or PIO.

d. Adequate performance.

1. Conventional approach and landing.

- Maintain approach angle within ±2 deg (or ±1 dot ILS).
- Maintain approach airspeed within ±10 kts.
- Touchdown zone:
  - 20 ft wide by 1000 ft long (Class I and IV aircraft).
  - 40 ft wide by 1000 ft long (Class II and III aircraft).
- Touchdown sink rate less than the gear limit (or no bounce and no hard landing if touchdown sink rate is difficult to measure).
- No tendency for sustained PIO.

2. STOL approach and landing.

- Maintain approach angle within ±2 deg (or ±1 dot ILS).
- Maintain approach airspeed within ±5 kts.

- Touchdown zone:
  - 20 ft wide by 100 ft long (Class I and IV aircraft).
  - 40 ft wide by 500 ft long (Class II and III aircraft).
- Touchdown sink rate less than the gear limit (or no bounce and no hard landing if touchdown sink rate is difficult to measure).
- No tendency for sustained PIO.

Precision offset landing (IMC/degraded visual environment)

a. Objectives.

- Check ability to precisely control horizontal and vertical flightpath and airspeed in a degraded visual environment.
- Check ability to precisely control sink rate and attitude in the flare in a degraded visual environment.
- Check tendency for nose bobble or PIO.
- Check control sensitivity and harmony in landing.

b. Description of maneuver. Initiate the maneuver approximately a 1.5 miles out on final approach with a lateral offset of up to 200 ft from the runway centerline and a vertical offset of upto 200 ft above glideslope with the gear and flaps up. The magnitude of the lateral offset should be such as to keep the runway within the available visual field-of-view. At the start of the maneuver, lower flaps and gear and capture the glideslope while maintaining the lateral offset. The approach angle (glideslope) shall be as appropriate for the aircraft being tested (roughly 3-deg for conventional approach or steeper for a STOL approach). At 300 ft AGL correct the lateral offset to land on the runway centerline with wings level. Touchdown within the prescribed touchdown zone with the aircraft centerline within the width of the zone and the main gear within the length of the zone. The task may be performed in any wind or turbulence conditions as allowed by the operational limits of the aircraft. Testing in extreme wind conditions (crosswinds and shears) is recommended. Additional constraints that are necessary for safety may be implemented as appropriate. For example, with Class III aircraft, restrictions may be placed on bank angles at low altitude.

c. Desired performance.

1. Conventional approach and landing.

   - Maintain approach angle within ±1 deg (±1/2 dot ILS).
   - Maintain approach airspeed within ±5 kts.
   - Touchdown zone:
     - 20 ft wide by 500 ft long (Class I and IV aircraft).
     - 40 ft wide by 500 ft long (Class II and III aircraft).
   - Touchdown sink rate less than 80% of the gear limit (or no bounce and no hard landing if touchdown sink rate is difficult to measure).
   - No tendency for pitch bobble or PIO.

2. STOL approach and landing.

   - Maintain approach angle within ±1 deg (or ±1/2 dot ILS).
   - Maintain approach airspeed within ±3 kts.
   - Touchdown zone:
     - 20 ft wide by 100 ft long (Class I and IV aircraft).
     - 40 ft wide by 200 ft long (Class II and III aircraft).

- Touchdown sink rate less than 80% of the gear limit (or no bounce and no hard landing if touchdown sink rate is difficult to measure).
- No tendency for pitch bobble or PIO.

d. Adequate performance.

1. Conventional approach and landing.

   - Maintain approach angle within ±2 deg (or ±1 dot ILS).
   - Maintain approach airspeed within ±10 kts.
   - Touchdown zone:
     - 40 ft wide by 2000 ft long (Class I and IV aircraft).
     - 80 ft wide by 2000 ft long (Class II and III aircraft).
   - Touchdown sink rate should be less than the gear limit (or no bounce/no hard landing if touchdown sink rate is difficult to measure).
   - No tendency for sustained PIO.

2. STOL approach and landing.

   - Maintain approach angle within ±2 deg (or ±1 dot ILS).
   - Maintain approach airspeed within ±5 kts.
   - Touchdown zone:
     - 40 ft wide by 200 ft long (Class I and IV aircraft).
     - 80 ft wide by 1000 ft long (Class II and III aircraft).
   - Touchdown sink rate less than the gear limit (or no bounce and no hard landing if touchdown sink rate is difficult to measure).
   - No tendency for sustained PIO.

Air-to-air tracking (high angle-of-attack)

a. Objectives.

- Check ability to stabilize on, and precisely track, a target at high angles-of-attack.
- Check for PIO tendency.

b. Description of maneuver. Initiate the maneuver with the test aircraft in 1-g level flight, approximately 1500 ft directly behind, and co-speed/co-heading with, a target aircraft. At the start of the maneuver, the target aggressively rolls and pulls to establish a constant (predetermined) angle-of-attack, constant (predetermined) airspeed, descending turn. The test aircraft rolls behind the target, goes to a lag position, and pulls to a stabilized tracking position at the test angle-of-attack. Track a point on the target as tightly as possible and conduct lateral and longitudinal 50 mil aimpoint corrections on the target. When angle-of-attack exceeds the desired range, break off, and attempt to regain a stabilized tracking position at the test angle-of-attack.

c. Desired performance.

- No PIO tendencies.
- Maintain pipper within ±5 mils of aimpoint for 50% of the task and within ±25 mils for the remainder of the task.

d. Adequate performance.

- Maintain pipper within ±5 mils of aimpoint for 10% of the task and within ±25 mils for the remainder of the task.

3. Relationship Between Demonstration Maneuvers and Stems

Because of the similarities in objectives, the results of the Standard Evaluation Maneuver Set (STEMS), developed by McDonnell Douglas Aerospace and the U.S. Air Force (Ref. C-9), were included in the research reported here. Since a considerable amount of effort has been expended on the STEMS, several of the maneuvers are candidate demonstration maneuvers with only a minimum of refinement. Most of this refinement consists of validation in an in-flight experiment, as opposed to a ground simulation.

There are 20 STEMS in the final maneuver set reported in Ref. C-9. The focus of STEMS was similar, but not identical, to that in this program. According to Ref. C-9, the STEMS maneuvers "augment rather than replace existing flying qualities evaluation techniques and are aimed primarily at expanded flight envelopes." They are aimed at both flying qualities and agility. As a result, there is a subset of STEMS that is directly applicable here, while several were found to not be usable as demonstration maneuvers.

Of the 20 STEMS, nine are considered to be evaluators of aircraft agility and performance, and in Ref. C-9 it is recommended that Cooper-Harper Handling Qualities Ratings not be taken. These nine STEMS are as follows:

STEM	Maneuver Title
4	Dual Attack
5	Rolling Defense
6	Maximum Pitch Pull
9	Pitch Rate Reserve
12	Loaded Roll Reversal
14	Minimum Speed Full Stick Loop
15	Minimum Time 180° Heading Change
16	1g Stabilized Pushover
17	J-Turn

The remaining 11 STEMS involve pilot evaluations and assignment of HQRs; most are also specifically geared toward high-angle-of-attack and high-g maneuvering. These maneuvers are considered likely candidates for demonstration maneuvers. The 11 STEMS, and the related MTEs from Table C-8 (if applicable), are as follows:

STEM	Maneuver Title	Table C-8 MTE
1	Tracking During High AOA Sweep	Gross acquisition using loaded roll
2	High AOA Tracking	Gross acquisition using loaded roll
3	High AOA Lateral Gross Acquisition	Gross acquisition using loaded roll
7	Nose-Up Pitch Angle Capture	Missile defense with loaded roll; Precision aerobatics
8	Crossing Target Acq. and Tracking	Tracking maneuvering target
10	High AOA Longitudinal Gross Acq.	Gross acquisition using loaded roll
11	Sharkenhausen	Gross acquisition using loaded roll
13	High AOA Roll and Capture	Missile defense with loaded roll; Precision aerobatics
18	Tanker boom tracking	In-flight refueling — receiver
19	Tracking in PA	In-flight refueling — receiver
20	Offset Approach to Landing	Precision landing

As this list indicates, almost half of these STEMS are considered to be most appropriate for a single MTE. After further evaluations, it is possible that one or more of the STEMS can be deleted from the list of demonstration maneuvers. If all of them are found to be important, however, all will be retained.

4. Demonstration Maneuvers, Performance Requirements, and Operational Utility

The development of the specific details of the Table C-8 demonstration maneuvers is beyond the scope of this Phase I effort. This development will require a careful consideration of the need for demonstration maneuvers that evaluate handling qualities and expose real handling-qualities deficiencies, while stressing the requirements for real-world operations, without imposing unrealistic performance demands on the aircraft. It would be easy, for example, to develop a demonstration maneuver whose performance requirements are greater than those specified for the aircraft in the original procurement. It would also be easy to contrive handling-qualities evaluations that have no real relationship to the actual uses for the aircraft, and therefore may be "exposing" problems that don't really exist.

In the detailed development of the demonstration maneuvers, every effort must be made to assure that the tasks and their related limits on desired and adequate performance reflect real-world operations. It would be appropriate, therefore, to involve the engineers and pilots who perform the flight testing as soon as possible.

D. REQUIREMENTS FOR VALIDATION OF DEMONSTRATION MANEUVERS

There are 27 Mission-Task-Elements in Table C-8. For some of these more than one possible demonstration maneuver is listed, while the same maneuver is repeated for others. Overall there are

approximately 30 candidate demonstration maneuvers. Some of these (such as cruise maneuvering) are amenable to checkout in a ground-based simulator. Others, however, will require in-flight evaluations for an accurate assessment.

It will be essential that at least one of the evaluation aircraft (if multiple aircraft are used) possess Level 1 handling qualities to determine the validity of the desired-performance limits. Ideally, at least one will also be solidly Level 2, since this will serve as a check on the adequate-performance limits.

1. Evaluations by the Air Force Test Pilot School

Refinement of the demonstration maneuvers listed in Table C-8 is an almost ideal endeavor for students of the Air Force Test Pilot School at Edwards AFB. Since there are no special requirements for a variable-stability airplane, aircraft in the Air Force fleet can be used in the evaluations. The maneuvers can easily be grouped into small packages and made part of the students' regular assignments. Pilot comments on the utility of each maneuver will be as important as pilot ratings, and the blend of operational experience and test-pilot training should serve this effort well.

It is envisioned that this phase of evaluations will parallel that taken by the TPS for the closed-quality testing reported in Ref. C-16. It is considered imperative that the predicted flying qualities of the test aircraft be known before the flight testing is initiated; thus Level 1 aircraft should achieve desired performance, Level 2 only adequate, etc.

2. Evaluations by the 4950th Test Wing

With the recent relocation of the 4950th Test Wing from Wright-Patterson AFB to Edwards AFB, it is possible that pilots from the 4950th could participate in the TPS evaluations. In addition, studies similar to that reported in Ref. C-40 (performed by the 4950th at Wright-Patterson) should be encouraged, assuming budget, time, and personnel requirements allow for them.

3. Evaluations by NASA Dryden Flight Research Center

An evaluation of the STEMS maneuvers is already planned by personnel at NASA Dryden. It is possible — again, depending upon personnel, budgets, and time — that further testing of other demonstration maneuvers may performed.

4. Evaluations on Air Force Simulators

As mentioned above, a number of the demonstration maneuvers may be developed on ground-based simulators. Examples include VMC and IMC maneuvering flight, especially for large (Class II or III) airplanes. A series of simulation sessions, using the transport simulator currently in development at Wright-Patterson AFB, will be extremely helpful in defining these demonstration maneuvers.

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APPENDIX D

UPDATES TO MIL-STD-1797A FOR SIDESTICKS

A. INTRODUCTION

The use of sidestick controllers in the advanced cockpit offers a number of distinct advantages over the traditional centerstick or yoke and column. With a side-mounted stick, the view of the instrument panel is completely unobstructed by the control column. Pilot ingress and egress are greatly enhanced, as is pilot comfort on extended flights. There is some additional benefit to be found simply from the reduced overall weight of the cockpit control actuation system. Based on these positive features, it is not surprising that sidesticks have found their way into the cockpits of all classes of aircraft, from the F-16 fighter to the Space Shuttle to the Airbus A320.

There are, however, some disadvantages as well. Most sidestick controls do not provide an equivalent level of tactile feedback to the pilot, and the limited displacements available to these sticks preclude the use of parallel trim systems. In addition, if the commanding signal from the stick to the aircraft's flight controls is pilot-applied force, it may be necessary to provide some prefiltering of this signal to prevent inadvertent and spurious acceleration commands. For transport aircraft, replacement of the traditional yoke — which allows control with either hand — with a single side-mounted sidestick — which can be controlled with only one hand — can also have implications on cockpit layout, switch access, etc. A major drawback with the use of the sidestick is that the state of the art in sidestick design is simply not as mature as that of the classical centerstick or yoke and column, resulting in a much greater likelihood of designing less-than-ideal characteristics into the controller.

This Appendix reviews all elements involved in the design of sidestick controllers, including their physical features, their force-response details, and their interactions with the responses of the aircraft. This review is intended to both update the information provided in the current military standard for flying qualities of piloted airplanes, MIL-STD-1797A (Ref. D-1), and to address related issues not discussed in MIL-STD-1797A. It will serve to illustrate the important elements in sidestick design as a prelude to defining the critical issues for handling qualities of sidestick-equipped aircraft.

This Appendix will introduce important factors for all classes of aircraft, including multi-crew transports, where the use of sidesticks raises concern over transferring of control and prioritization of command inputs. Topics discussed consist of the following:

- A brief history of sidesticks and sidestick research efforts;
- Stick physical design and cockpit orientation;
- Breakout and limiting control forces;
- Force/deflection and force/response characteristics;
- Use of artificial force feel;
- Force vs. position sensing requirements;
- Analysis of recent sidestick data; and
- Operations in a two-pilot environment.

Following these discussions a detailed review of the relevant requirements from MIL-STD-1797A will be given, including recommendations for new and upgraded requirements.

B. HISTORY

Sidestick controllers are not necessarily confined only to advanced, fly-by-wire aircraft. With the advent of boosted controls, it is possible to replace the conventional controls in any current-day aircraft with sidesticks. The use of sidesticks in aviation actually dates back to the original Wright Flyer, which used a single-axis pitch-control stick. Development of sidesticks has continued on an irregular basis ever since; Ref. D-2 provides a concise history of the evolution of the sidestick for airplanes.

The first operational sidestick was installed in the experimental X-15 rocket aircraft, which included both a centerstick and a sidestick, mechanically coupled so that either could be used at any time. The Space Shuttle also employs a sidestick. The first sidestick-controlled regular-production airplane was the Air Force's F-16. The early difficulties encountered with this stick, a rigid, force-sensing controller, led to considerable experimental work in both the F-16 and other research aircraft to find ways to improve the F-16's controller (e.g., Appendix C of Ref. D-3). The details of the early and more recent stick characteristics for the F-16 are used throughout this working paper for comparison purposes.

Considerable progress has also been made in the development of sidesticks for helicopters, primarily as an element in the design program for the Army's next-generation attack helicopter, the RAH-66 Comanche. Sidestick configurations for helicopters include integrated control of two axes (pitch and roll), three axes (pitch, roll, and either yaw or heave), and all four axes, on one stick. Some of the research data from this development process (e.g., Refs. D-4 through D-7) will be introduced throughout this Appendix paper as warranted.

The most recent, and most celebrated, usage of sidesticks is in the Airbus Industrie line of advanced commercial transports, the A320 and A340. Little published data is available on the specifics of these controllers; some information has been gleaned from various sources and is used in this Appendix for comparison with the design guidelines.

The most significant source of quantitative data on sidestick controllers comes from a series of flight tests sponsored by the U.S Air Force on the variable-stability NT-33A research airplane in the 1970s. These studies, most of which were performed by students at the Air Force Test Pilot School, focused primarily on the interactions of stick force/deflection and force/response gradients with aircraft dynamics in pitch and roll. Some of the TPS results were available when the draft military standard was written (Ref. D-8), so they were included in the Ref. D-1 standard and will be mentioned as appropriate. Detailed analysis of the results from more recent experiments are included in Section F of this Appendix.

MIL-STD-1797A has no information at all on the requirements for sidestick-controlled transport (Class III) aircraft. There have been very few studies of the requirements on sidestick design for transports; one published report (Ref. D-9) includes assessments of different cockpit control arrangements in a B-26, but it unfortunately does not contain a complete description of the sidestick controller, so it is difficult to obtain any quantitative information. A simulation and flight test program to develop a fly-by-wire flight control system for the C-141 (Ref. D-10) included a sidestick, but again, there is incomplete documentation on the characteristics of the stick used. There have been no published reports of back-to-back handling qualities evaluations of conventional vs. sidestick controls for transports.

C. PHYSICAL DESIGN AND COCKPIT LOCATION CONSIDERATIONS

Physical design of the stick and its orientation in the cockpit can have as profound an effect on pilot acceptance as its response characteristics. Unfortunately, the information on pilot preference is entirely anecdotal: studies of sidestick characteristics typically do not include evaluations of the design and orientation of the stick itself. Instead, it is necessary to compare stick designs and determine those characteristics that have been received most favorably by the pilots.

As a part of its initial design studies for an Advanced Digital/Optical Control System (ADOCS) for an advanced helicopter, Boeing Vertol conducted a thorough review of stick design characteristics and requirements (documented in Volume 2 of Ref. D-4). This study provides a good summary of the issues involved in sidestick controls, and it will be referred to here as a prime source of information.

1. Grip Design

The shape of the stick grip is a major factor in pilot acceptance of sidesticks. A grip shape that is incompatible with the aircraft response – for example, a small-diameter "pencil grip" for an aircraft that is very sluggish – will result in an unacceptable aircraft. According to a study of sidestick characteristics for general aviation aircraft (Ref. D-11), "The pilots suggested a preference for the shape of the stick handle dependent on the force gradient and the difficulty of the task. A full hand grip design was preferred for heavy forces and/or difficult tasks. A finger tip design was desired for light forces and/or easy tasks."

Most sidestick grips are very similar in appearance to those for centersticks. Unusual designs have been applied, such as a finger/ball grip controller on the Boeing Vertol Heavy Lift Helicopter (HLH). This controller required very light grip with the fingertips and thumb, and only small inputs were necessary for control. It was used for operations during cargo handling on a highly augmented helicopter, and for this application was generally found acceptable (Ref. D-5).

A somewhat similar design, with a ball in the center of a stick grip, is installed in the U.S. Army's Crew Station Research and Development Facility (CSRDF), a fixed-base helicopter simulator. Pilots who are familiar with this stick report that it takes considerable training time to learn how to apply extremely light, fingertip control. Inadvertent cross-axis inputs are common; some pilots feel that this stick design would be totally unacceptable in a motion environment.

In a study in support of the Ref. D-4 development effort, Honeywell provided several recommendations to Boeing Vertol for proper grip design. From Ref. D-4, the grip must:

- Have finger depressions along its front surface to position the hand with respect to the grip's top and bottom.
- Position the thumb and index finger approximately parallel to each other, permitting immediate tactile and visual awareness of the grip's position within the hand with respect to rotation about its longitudinal axis.

2. Location Relative to the Pilot's Seat

Location of the stick relative to the pilot's seat can have subtle, but important, effects on pilot acceptance. Given that the stick will be permanently located within the cockpit, the pilot's only available means for locating an optimal position relative to the stick is adjustment of the seat and, if provided, the stick's armrest.

Reference D-6 reports on a study of anthropometric considerations for sidestick location and orientation. This study did not consider the dynamics of the controller itself; it merely evaluated the results of pilot preference in a static cockpit environment. Reference D-6 found, for example, that the preferred forward stick locations for a sample of 52 male personnel (non-pilots) varied over a range of less than 9 inches. For 18 female non-pilots, the range was even smaller, less than 5 inches. The range of preferred vertical locations was 7 inches for male and only 3 inches for female personnel. These small preferred adjustment ranges emphasize the need for relatively careful initial installation of the stick in the cockpit, and of the seat and armrest relative to the stick.

An adjustable armrest is essential. According to Ref. D-11, "The vertical position of the hand is dictated by the necessity to firmly rest the forearm on the armrest.... An operational side stick should have a variable control stick length or armrest height to allow precise control of the position of the top of the control stick and the position of the pilot's hand." A sidestick should never be used without some support for the forearm to reduce pilot fatigue during extended manual operations. In addition, if the aircraft's cockpit control and response characteristics were designed assuming the pilot's arm is supported, flying without the support runs the risk of inadvertent pilot inputs from the "arm-bobweight" effect of the unrestrained arm; on highly responsive aircraft, such effects have been found to be related to the pilot-vehicle high-frequency oscillation referred to as "roll ratchet" (Ref. D-13).

Vertical orientation of the upper arm should also be considered for pilot comfort. In the Ref. D-11 study of sidestick designs for general aviation aircraft, "The pilots considered the angle of the upper arm to be important for adequate control and comfort. The vertical or near vertical position of the upper arm was preferred.... This may require that the stick location/position be adjustable to encompass the typical wide range of pilot physical characteristics."

The vertical location of the armrest relative to the stick, and perhaps even the angular orientation of the armrest, should be available for adjustment. In the Ref. D-6 study, there was a preference (in terms of comfort alone) for the armrest tilting upward slightly toward the stick (i.e., wrist higher than elbow): the range of selected angles was 4° down to 16° up, with a mean tilt angle of 7.5°. It is likely that the pilot will accept any armrest angle in this range, as long as the stick position itself is comfortable. Two sidestick configurations were evaluated in the ADOCS helicopter simulation study (Ref. D-4), one with an upward tilt of 12° and the other with 2° down. No adverse pilot comments are reported for either orientation.

A final consideration in stick location, alluded to earlier, deals with the layout of the cockpit itself. With a traditional centerstick, and even more with the yoke and column arrangement of most transports,

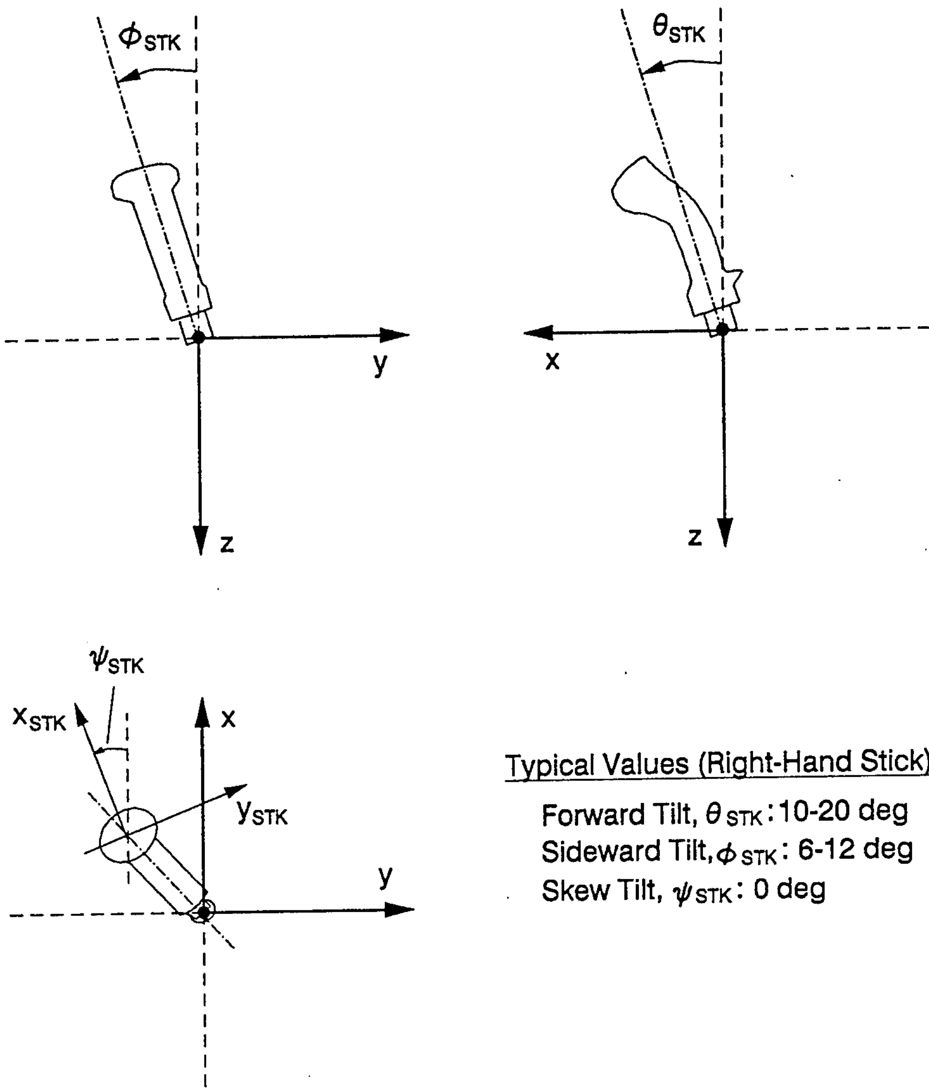
the pilot can, for short periods of time, manually control the aircraft with either hand. This allows for full access to switches and knobs within the reach of the pilot. With a single side-mounted stick, however, the pilot flying is restricted in cockpit access; for example, for a right-mounted stick, the pilot will not be able to operate any cockpit functions located to the right of the stick, unless the pilot is willing to momentarily relinquish manual control. In critical stages of flight, therefore, there should be absolutely no requirement for the pilot to reach cockpit switches that would involve relinquishing control.

An obvious, but unappealing, solution to the cockpit access problem is to simply install dual sidesticks. In a human-factors study of possible control arrangements by pilot evaluators (Ref. D-14), this was the preferred layout since it provides the pilot with either-hand operation. Such sticks also allow for direct mechanical coupling, providing the pilot with immediate feedback if there is a failure of the control system, but they greatly diminish the positive effects of cockpit space reduction, and may prove a problem during manual control of both attitude and throttles, since one stick would hinder access to the throttle controls.

3. Orientation and Neutral Position

There are three variables in defining controller neutral position: fore/aft (pitch) tilt, left/right (roll) tilt, and twist (or skew of the yaw axis), as illustrated in Fig. D-1. All available data show a preference for some forward pitch tilt and inboard roll tilt (i.e., left tilt for a righthanded stick when viewed by the pilot, Fig. D-1). In terms of purely static position for comfort, the anthropometric study of Ref. D-6 indicates a pilot preference for about 8° forward and 6° inboard tilt. These angles are, however, reflective of the natural resting position of the hand; in actual operation, pilots prefer to have the stick slightly more forward of the hand's natural neutral position, because aft wrist rotation from this position is very limited. In addition, aft inputs are much more common than forward inputs, so a slightly greater forward tilt allows some aft wrist freedom.

Figure D-2 shows the neutral positions and deflection ranges for several sidesticks. All of the sticks shown have some forward tilt, ranging from 8° (the ADOCS simulation controller, Ref. D-4) to 20° (the A320, Ref. D-15). Inboard tilt varies from zero deg (the NT-33A flight research aircraft stick, Ref. 16) to 12° (the A320, Ref. D-15, and the F-104 SSCS, Ref. D-12). According to Ref. D-12, the pilots selected 12° inboard "because of the limited freedom of the human forearm to rotate in the outboard direction. We have found that aircraft control deteriorates if the pilot's hand is beyond 5° to 8° [outboard]... of vertical."



Typical Values (Right-Hand Stick):

Forward Tilt, θ_{STK}: 10-20 deg
Sideward Tilt, ϕ_{STK}: 6-12 deg
Skew Tilt, ψ_{STK}: 0 deg

Figure D-1. Preferred Sidestick Orientation Relative to Aircraft Body Axes (x,y,z)

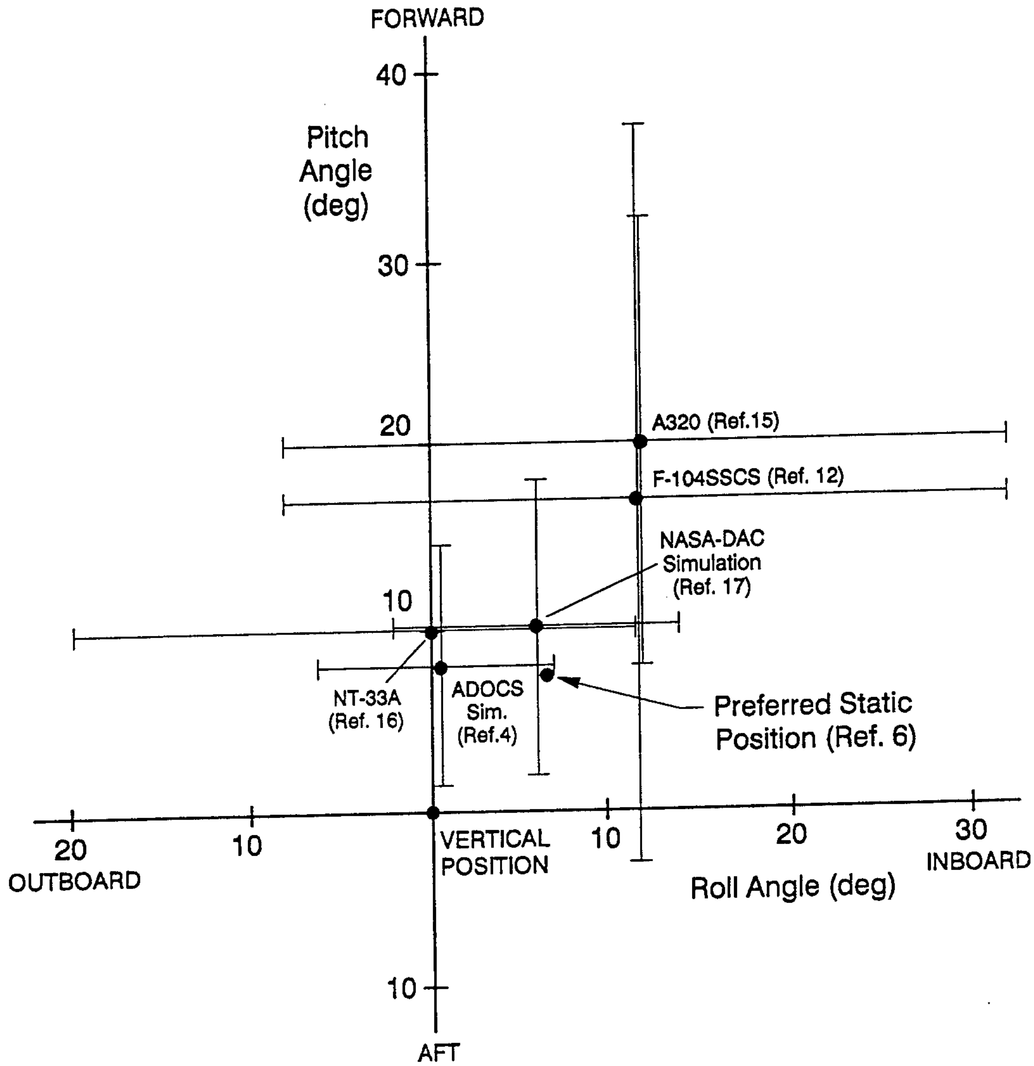


Figure D-2. Neutral Positions and Deflection Ranges of Several Sidesticks

Neutral position will, of course, be a function of the deflection range of the stick; with a small-deflection stick, the neutral position can be closer to the human's natural hand resting position, as it is for the ADOCS simulation, NT-33A flight research aircraft, and NASA-Douglas Aircraft Co. simulation (Ref. D-17) sticks in Fig. D-2. With larger deflections, the neutral position should be further forward and more inboard than this, as it is for the F-104 SSCS and A320 sticks in Fig. D-2.

Twist of the stick, or skewing of the axes from the aircraft's centerline, has also been used for some sidesticks. This may be especially necessary when the stick possesses a limited deflection range or unusual breakout, force/deflection, or pitch-roll harmony characteristics. In the case of limited deflections, the natural twist of the hand may lead to inadvertent cross-axis inputs because of a lack of tactile cues. Unusually high or low breakouts, or poor pitch-roll control harmony, may also result in unintentional cross-axis inputs. Such inputs can be alleviated by skewing the stick to counter the wrist's natural twist. The study of Ref. D-6 found that the subjects preferred to rotate their wrists about 15° further inboard than the twist of the stick handle itself. From this orientation, an aft input that may be perceived by the pilots as purely longitudinal may, in fact, induce a slight lateral input as well. The solution is to skew the stick axes so that the yaw axis is outboard by a roughly equal amount. In a comprehensive study to improve the characteristics of the limited-motion F-16 sidestick (documented in Appendix C of Ref. D-3), an axis rotation of 12°, in combination with reduced stick forces, "improved the overall aircraft handling qualities. Takeoff and landing were considered more comfortable; an improvement which was attributed specifically to the skewed axes. Crosstalk during takeoff, landing and formation flying was reduced; the amount of reduction varied from pilot to pilot." The F-16's controller has many unique characteristics that affect the significance of the axis skewing; for more conventional forces and force/deflection designs, such skewing is probably not necessary, and might even detract from the overall controllability of the aircraft. Axis twist or skewing should generally not be considered.

4. Pivot Point

As is shown later in this Appendix, some motion of the controller is essential for response cue feedback to the pilot. The location of the pivot point affects pilot comfort and precision of control.

The two most common pivot points for sidesticks are base pivot (pivot point below the hand grip) and wrist pivot (pivot point located near the center of the hand grip). These arrangements are illustrated in Fig. D-3. The wrist pivot has been applied to controllers for spacecraft, including Apollo and the Space Shuttle. Figure D-4 shows the functions of two rotational hand controller designs from the Apollo Command Module (Ref. D-18); both use a wrist pivot for pitch control and base pivot for roll control.

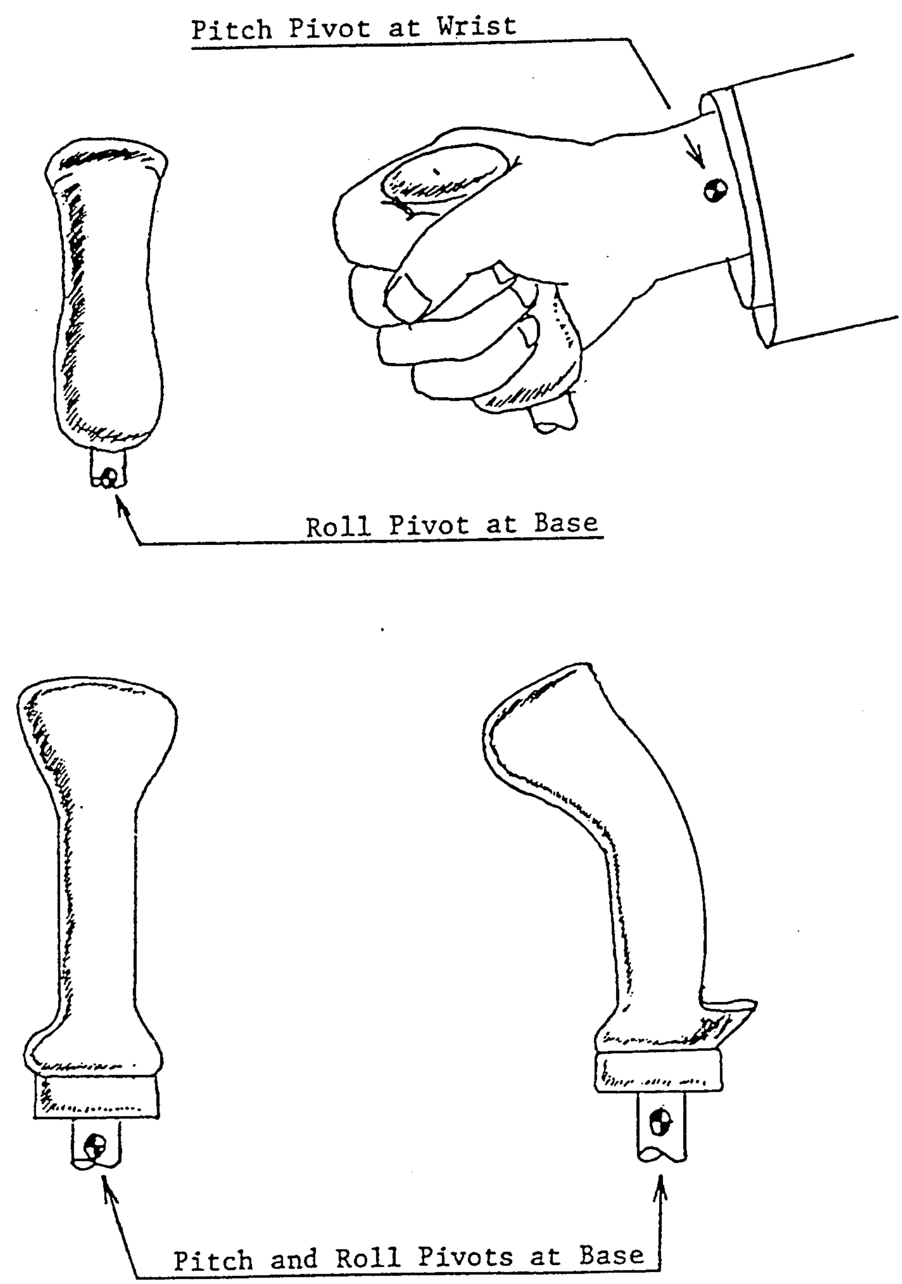
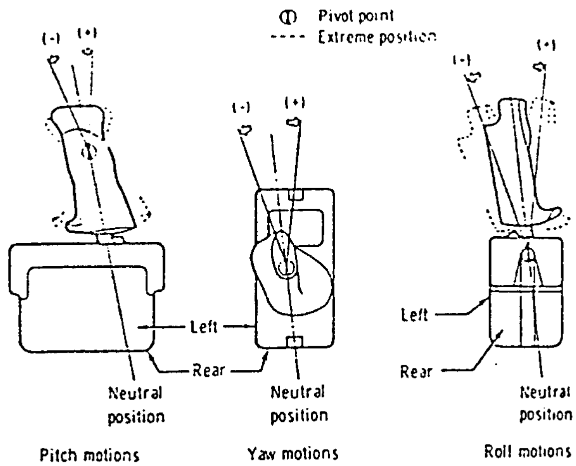
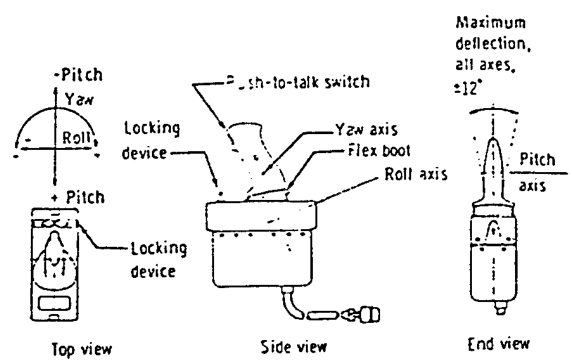
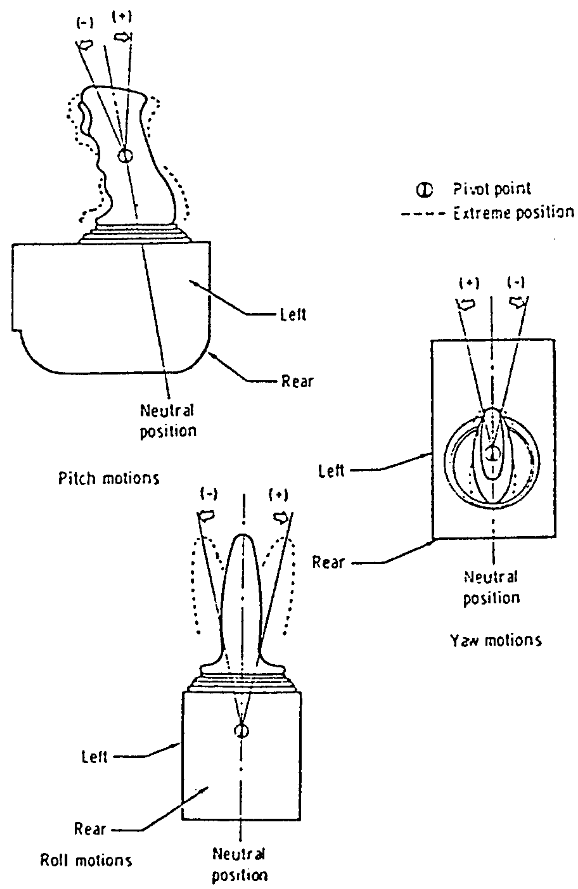


Figure D-3. A Comparison of Two Pitch and Roll Pivot Locations Sets
(from Ref. D-2)



a) Functions of the Block I Rotational Hand Controller





b) Functions of the Block II Rotational Hand Controller

Figure D-4. Apollo Command Module RHC Physical Configurations

This configuration has been reported to be less than ideal as a result of the unnatural up-and-down motion of the wrist (Ref. D-2).

Base pivot distance below the fist (measured roughly from the middle finger) typically varies between four and eight inches for most current sidesticks.

5. Stick-Mounted Switches and Buttons

Stick-mounted buttons, such as push-to-talk and trim buttons, must have some motion associated with their activation (Ref. D-12). Pilots require some indication of physical movement, and positive "click" buttons should be used. In addition, according to Ref. D-12, "The forces required to actuate a switch must be significantly, at least 50%, below the breakout forces of the controller itself. If this is not true, the pilot places spurious inputs to the control stick each time he actuates the switch."

The Airbus A320 control system reduces the demands on stick buttons by providing a self-trimming rate-command control law, thus eliminating the need for a trim button (Ref. D-15).

D. FORCE, DEFLECTION, AND RESPONSE CHARACTERISTICS

The characteristics of sidesticks to be considered here include breakout forces, limit control forces, and force/deflection versus force/response gradients. This discussion will draw heavily from flight research data presented in MIL-STD-1797A and in Section F of this appendix. There is almost no quantitative flight test information for transport aircraft in these subject areas; the small amount of data available from a single fixed-base simulation (Ref. D-17) is reviewed in Section F.

1. Breakout Forces

Selection of the proper level of stick breakout forces depends on the force characteristics beyond the breakout and the force requirements for operation of stick-mounted buttons. Some level of breakout and positive centering is as important for sidesticks as it is for wheels and centersticks, but too much breakout must be avoided. For example, an excessively large breakout, followed by light stick forces, will lead to overcontrol; by contrast, a very low breakout will increase the possibility of inadvertent control inputs when a stick-mounted button, such as the push-to-talk button or trim switch, is depressed. In the latter case, a reduction in the force required to activate the buttons will alleviate the problem somewhat, but will also make inadvertent button operation more likely.

The solution is to carefully select the breakout forces in pitch and roll to be harmonious with the response characteristics of the aircraft. High breakout forces can be tolerated for wheel controllers, where two-handed operation may be applied at times and where the pilot can apply full arm motion to the wheel and column. Lower breakouts are required for centersticks, and sidesticks may justify yet lower values of breakout force. In MIL-STD-1797A (Ref. D-1), breakout forces for wheel-controlled transports can vary between 1/2 lb and 7 lb for pitch, and between 1/2 lb and 4 lb for roll. By contrast, MIL-STD-1797A requires sidestick breakouts to be between 1/2 and 1 lb. Based on a review of the available literature, the current 1797A numbers seem reasonable, though a slightly higher maximum force may be acceptable for transports. Higher breakouts have been used; for example, the F-16 stick has 1.75 lb of breakout in both pitch and roll. But this stick, which is effectively rigid (maximum displacements of less than 0.2 inch) and for which the command signal is sensed applied force, may require a higher breakout to reduce the likelihood of inadvertent pilot inputs. In the F-104 SSCS study of Ref. D-12, breakout force varied with the three different levels of force/deflection gradient that were evaluated; the best force/deflection curves resulted in breakout forces of 3.1 lb in pitch and 2.2 lb in roll, and there are no adverse comments about these forces in Ref. D-12.

Lighter stick forces have been shown to be preferable to heavy forces. In a USAF Test Pilot School flight research program using the variable-stability NT-33A, reported in Appendix A of Ref. D-2, an increase in breakout forces from 1/2 lb to 1 lb resulted in "an increase in pitch sensitivity" and slightly degraded handling qualities. Most evaluations on the NT-33A have been performed with 1/2-lb breakouts; Ref. D-16 is an exception, with 1-lb breakouts, and there were no obvious adverse comments. Both the Space Shuttle and the A320 have relatively light breakout forces. The Shuttle's roll breakout force is about 0.7 lb, while the A320 has 0.79 lb in pitch and 0.67 lb in roll.

In summary, it appears that breakout forces for sidesticks should be in the range of 1/2 lb to 1 lb, though slightly higher forces of about 2 lb or less may still be acceptable.

2. Limit Control Forces and Deflections

As with all the force characteristics, the acceptable maximum control forces are related to all other force, deflection, and response parameters. For recommendations on limit control forces, we can make use of the analysis in Ref. D-2. In this report an envelope for limits on "normalized deflection/force gradient" is presented. This gradient is in units of 1/lb, defined as deflection/force gradient (in./lb) divided by maximum deflection (in.); it is simply the inverse of limit control force:

$$\text{Normalized Gradient} = \frac{\delta/F \text{ (in./lb)}}{\delta_{max} \text{ (in.)}} = \frac{1}{F_{max} \text{ (lb)}}$$

Inverting the boundaries of this envelope produces a corresponding envelope for limit forces for sidesticks, as shown in Fig. D-5. This boundary shows that there is a relationship between limit forces in pitch and roll, as is expected for control harmony. The limit forces for several aircraft are shown for comparison in Fig. D-5. The F-16's two sticks, the early fixed stick and the current movable stick, have asymmetric fore-aft limits, as shown (Appendix C of Ref. D-3), and all forces lie in or near the boundaries. The Measurement System, Inc. (MSI) sidesticks evaluated on the ADOCS helicopter simulation (Ref. D-4) and on the National research Council of Canada's NAE Bell 205 variable-stability helicopter (Ref. D-7) are both on the limits. The A320 uses asymmetric roll control forces, with lower forces for outboard control (i.e., left roll commands for a left-handed stick) than for inboard control. The inboard forces are within the roll limits while the outboard value is below the boundary. Based on Fig. D-5, the limit forces for sidesticks should be no greater than about 33 lb in both pitch and roll.

The sidestick limits of Fig. D-5 are compared with force limits for other controllers from MIL-STD-1797A and from FAR 25.143(c) in Fig. D-6. The temporary-application limits of FAR 25.143(c) are identical to limit forces for Level 2 flying qualities from MIL-STD-1797A. The highest limit pitch force for wheels in MIL-STD-1797A is for dives and recovery from dives (paragraph 4.2.8.6.2 in Appendix A of Ref. D-1), 75 lb; and the limiting roll control force comes from rolling performance requirements (paragraph 4.5.9.2), at 60 lb. The centerstick requirements in MIL-STD-1797A are much lower, since only one-handed operation is possible, with limits of 50 lb and 30 lb, respectively (Fig. D-6). The sidestick upper force limits are close to those for the centerstick in Fig. D-6; this is as expected, since both involve one-handed operations.

Minimum and maximum deflections are directly related to forces through the force/deflection gradients, discussed next. Excessively small deflections — such as the F-16 "fixed stick" — deny the pilot of an essential tactile cue; excessively large deflections become uncomfortable for the pilot. The ultimate limits on control deflection are dictated by the combination of limit control forces and force/deflection gradients; based on Fig. D-4, however, we can infer that deflection ranges of about ±8° to ±20° are acceptable. The size of this deflection range is highly dependent upon the initial neutral position of the stick.

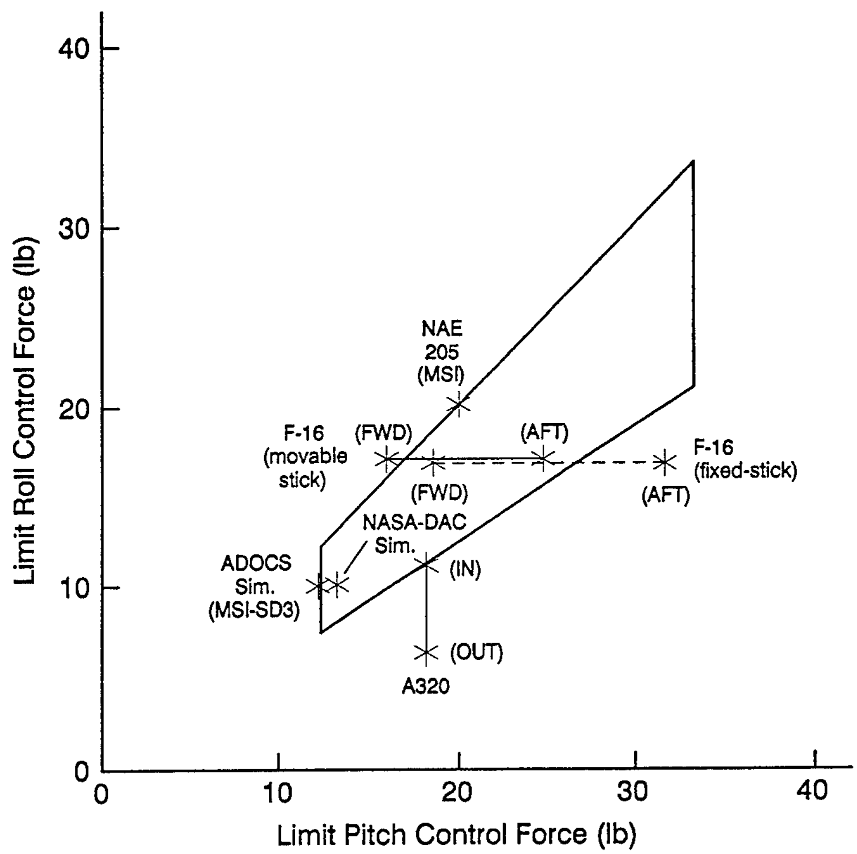


Figure D-5. Recommended Limits on Pitch and Roll Control Force

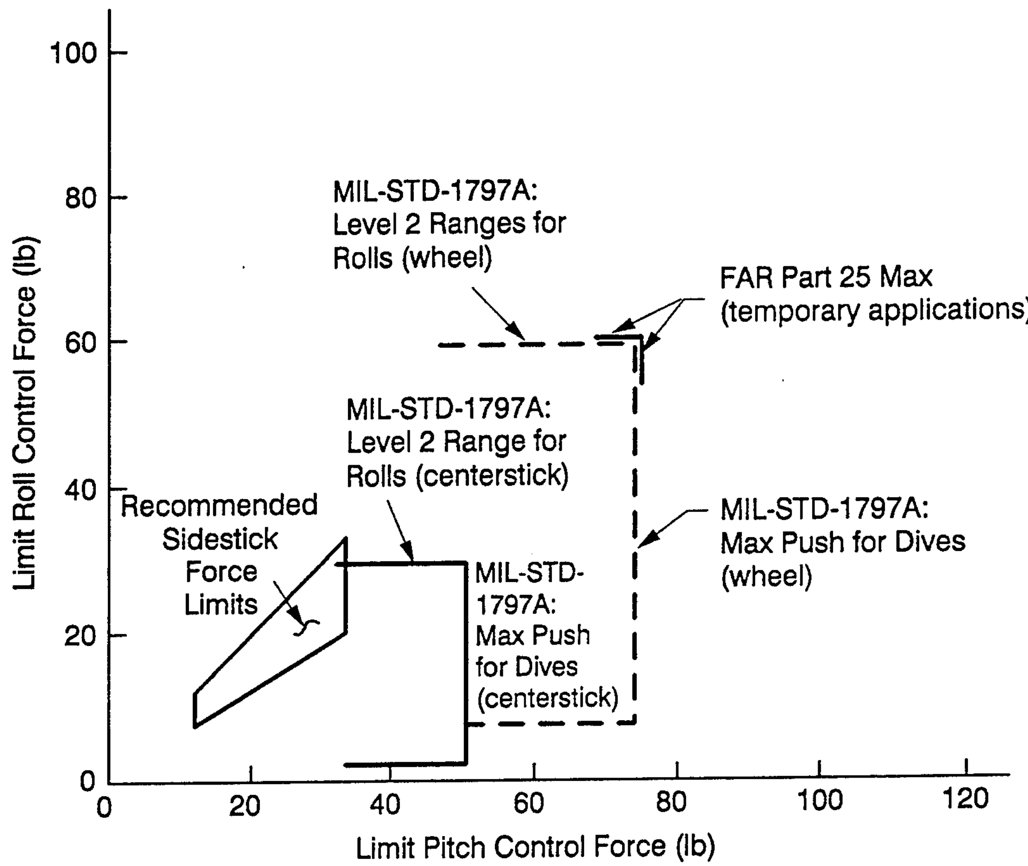


Figure D-6. Comparison of Control Force Limits

3. Deflection/Force and Force/Response Characteristics

Deflection/force gradient, typically measured in units of deg/lb, determines the amount of tactile feedback provided to the pilot in maneuvering. (This gradient is sometimes expressed in terms of force/displacement gradient, in units of lb/in., for non-rigid controllers.) In combination with limit control force, it also specifies the maximum deflection of the controller. Sticks with little or no deflection, so-called "stiff sticks," have proven to be less than desirable in flight. The original "fixed stick" on the F-16 had maximum travels of only 0.032 inches in pitch and 0.045 inches in roll. The resulting force/displacement gradients were 975 lb/in. (deflection/force gradient of 0.008 deg/lb) and 378 lb/in. (0.216 deg/lb), respectively. The "movable" F-16 stick has maximum travels of 0.2 inches in pitch and 0.13 inches in roll, resulting in gradients of 125 lb/in. and 134 lb/in., respectively. By contrast, the Space Shuttle has a roll gradient of about 2.2 lb/in., or 5.8 deg/lb.

There have been numerous flight research studies of requirements on deflection/force and force/response characteristics. The results of these studies are analyzed in detail in Section F of this Appendix.

4. The Use of Artificial Force Feel

Artificial force-feel systems are essential in stick- and wheel-controlled aircraft. The level of sophistication of such feel systems depends upon the purpose of the feel system itself. For high-performance fighters, the very large envelope of airspeeds and altitudes demands some form of force feel. Force feel for transports is also important, but is typically relatively simple in design, for the conventional column and wheel. Some form of artificial force-feel system may also be employed on the sidestick; with very stiff sticks, such as that on the F-16, "force feel" is not needed since the stick has almost no deflection. For larger deflection ranges, force feel may be used to enhance the tactile information provided to the pilot. It can also serve to smooth the pilot's inputs, since force feel is effectively a stick filter.

The governing equation relating stick force, F, and position, x, is

$$F = I\ddot{x} + b\dot{x} + kx$$

where I is the stick inertia, b is the stick damping, and k is the spring gradient. Dividing by I, we see that the more familiar second-order damping ratio and natural frequency are given by

$$2\zeta_{FS}\omega_{FS} = b/I \text{ and } \omega^2_{FS} = k/I$$

or

$$\zeta_{FS} = b/\sqrt{4Ik},\ \omega_{FS} = \sqrt{k/I}$$

The damping ratio should always be greater than about 0.3; a reasonable upper limit has not been found, but is probably near unity. Requirements on stick natural frequency and effective stick inertia have not been determined for sidestick controllers. It is reasonable to expect, however, that these numbers will not be radically different from those for centersticks. Reference D-20 investigated damping and frequency limits for centersticks and recommended that the stick natural frequency be greater than about 10 rad/sec for acceptable handling qualities. Lower natural frequencies may be acceptable if the effective stick inertia is less than about 5 lbm.

E. OTHER CRITICAL ISSUES FOR USE OF SIDESTICKS IN THE ADVANCED AIRCRAFT

There are issues in sidestick control application and design that deal specifically with their use in the advanced aircraft. These consist of the interaction of stick characteristics with the dynamics of the aircraft and the choice of force or deflection sensing for commands.

1. Aircraft Response Dynamics

With the use of extensive augmentation, it is possible to tailor the dynamics of the aircraft, in terms of both rapidity of response and response type, over the entire flight profile. As an example, attitude response-types are preferable for landing; such response-types require the pilot to either apply constant aft stick forces in the flare, or trim off the forces. A stick with very large deflection characteristics will not be desirable since it may also require unusual or uncomfortable hand/arm positions during the flare.

There is also evidence that the range of acceptable force/response gradients varies with short-period frequency (Ref. D-2): the higher the short-period frequency, the higher the desired stick force per g. This relationship would be a consequence of the more rapid response from the higher short-period frequency, since heavier forces naturally suppress pilot overcontrol tendencies. More thorough analysis of all sidestick data, presented in Section F, does not show this relationship, however.

2. Stick Force vs. Deflection Sensing

With a fly-by-wire control system, electrical signals are sensed from the cockpit controls and transmitted to the aircraft's onboard computers. These electrical signals may be either control deflection or control force. Force sensing is mandatory for sticks with very limited motion, such as that in the F-16 (Ref. D-3). With large motions, either force or displacement may be used as the control command. There are advantages and disadvantages with either mechanization.

If a force-sensing controller is used, the command signal is unfiltered by any artificial force-feel system since the pickoff is outside of the feel system. As a result, force controllers provide an extremely high control input bandwidth. On the other hand, this means that the signal is susceptible to inadvertent large pilot inputs, such as through vibration, or to sudden changes in force, such as occurs if the stick is released. To safeguard against these problems, some prefiltering or limiting of the command signal is required. It is most common to apply a high-frequency first-order filter to the sensed force signal, typically in the range of 8 to 16 rad/sec. Another approach (e.g., Ref. D-4) has involved the used of a derivative rate limiter that effectively acts as an acceleration limit. Either approach results in some smoothing of the pilot's inputs, thus acting as a filter and hence reducing the differences between force and displacement sensing.

In the absence of appropriate filtering, and with unusually high command gains and response dynamics, roll ratcheting has occurred during rolling maneuvers (Refs. D-20 and D-21). Roll ratcheting is more common with force-sensing sticks, though displacement sensing controllers have also produced the phenomenon. It is unlikely to occur in an aircraft with properly designed command and response characteristics.

Many of the potential problems with force-sensing controllers may be avoided entirely by simply choosing instead to use displacement commands.

F. ANALYSIS OF RECENT SIDESTICK DATA

1. Sources of Data

A series of sidestick research flight experiments was conducted by students of the Air Force Test Pilot School in the late 1970s and early '80s. The research, performed on the USAF variable-stability NT-33A, represents the best source of information on sidestick characteristics. This data is limited to fighter-type aircraft, and there is a generally large interpilot variation in ratings, due possibly to a combination

of lack of experience in the evaluation process and the conduct of flight maneuvers with no clearly defined desired and adequate performance requirements. Examples of these variations in pilot ratings are examined in this section as the data are analyzed in detail.

The first data set from the NT-33A comes from experiments conducted by Calspan in 1975 (Ref. D-16). Results of five TPS experiments were analyzed in Ref. D-2 and were summarized in appendices in that report. Data from these experiments were also included in the draft MIL Standard and Handbook (Ref. D-8), and hence appear in Appendix A of MIL-STD-1797A (Ref. A-1). Not included in these references are data from three later experiments, Refs. D-22, D-23, and D-24. The only concise data base for transport airplanes comes from a fixed-base simulation experiment, Ref. D-17.

This section reanalyzes the data included in Ref. D-1 to evaluate some of the specific requirements of 1797A.

2. Requirements on Deflection/Force and Force/Response Gradients

a. Definitions

Deflection/force gradient, typically measured in units of deg/lb, determines the amount of tactile feedback provided to the pilot in maneuvering. The range of acceptable force/deflection gradients is related to the force/response gradient of the aircraft. In pitch this gradient is expressed in terms of pounds of stick force per achievable incremental load factor in g, while in roll it is more useful to express the gradient in terms of response/force, in units of deg/sec of roll rate per pound.

A more detailed discussion of stick deflection/force and force/response characteristics was presented previously in Section D of this Appendix.

b. Linearity of Gradients

Design of deflection/force and force/response gradients requires a balance between the requirements for low initial sensitivity and high control power. In any phase of flight, the use of a single gradient is unlikely to satisfy both of these requirements. Nonlinear gradients are commonly used; typically, in flight testing these gradients have been limited to two-slope functions only, though more sophisticated networks may be acceptable. For all of the flight experiments discussed in this appendix, dual-slope gradients were used in both pitch and roll.

An example of the pitch and roll gradients for up-and-away (Category A) operations is shown in Fig. D-7. The pitch gradients (top figure) reduced by 50% for control force above 4 lb; in roll (bottom figure), a 50% reduction occurred at 3 lb. In one of the experiments reported in Ref. D-2, gradients of 4:1 and 6:1 were evaluated, in addition to the standard 2:1. The higher gradients were considered too abrupt, and all other TPS experiments used 2:1 exclusively.

c. Class IV (Fighter) Data

For this analysis, all applicable data from Refs. D-2, D-16, D-22, D-23 and D-24 will be used. Several assumptions and overall observations must be stated before the data are introduced.

In most of the experiments, pitch and roll gradients were varied simultaneously (e.g., force combinations labeled L through VH in both parts of Fig. D-7), and the HQRs assigned were overall ratings. This makes it difficult to discern which axis might be the source of handling qualities deficiencies. For this reason it is important to assess both the pitch and roll gradient variations together.

Because of the dual-slope gradients evaluated (e.g., Fig. D-7), it would be misleading to reference the data to either of the gradients. The evaluation maneuvers in all of the experiments emphasized maneuvering at elevated load factors. For up-and-away evaluations, air-to-air tracking tasks usually included 2-g turns and reversals, 2-g loaded rolls, and wind-up turns to between 3 and 4 g. Based on these maneuvers, it seems reasonable to consider the pitch force required to achieve a 2 g load factor, regardless of the gradient(s) used to get there. (Since this is a 1-g incremental load factor from 1-g flight, it also corresponds to an effective response gradient.) For all but Ref. D-16, breakout force was 0.5 lb (Ref. D-16 used 1-lb breakouts), so the breakout force was subtracted from the force to achieve 2 g in all cases.

For landing, the landing flare requires a relatively large pitch control input, but otherwise inputs are small perturbations from trim. In this case, the initial force gradient (again, with breakout force removed) is used.

In both up-and-away and landing, the nature of the tasks was such that only small roll rates were required, especially for fine attitude control in the tracking tasks. Maximum roll rates were typically less than 30 deg/sec. In this case the initial response gain above breakout is appropriate.

The pilot ratings from all of the relevant flight experiments show considerable interpilot scatter and a clustering of ratings around a very small range. This is illustrated by a series of interpilot rating comparison plots, presented in Fig. D-8. These plots are not meant to be an exhaustive analysis of the

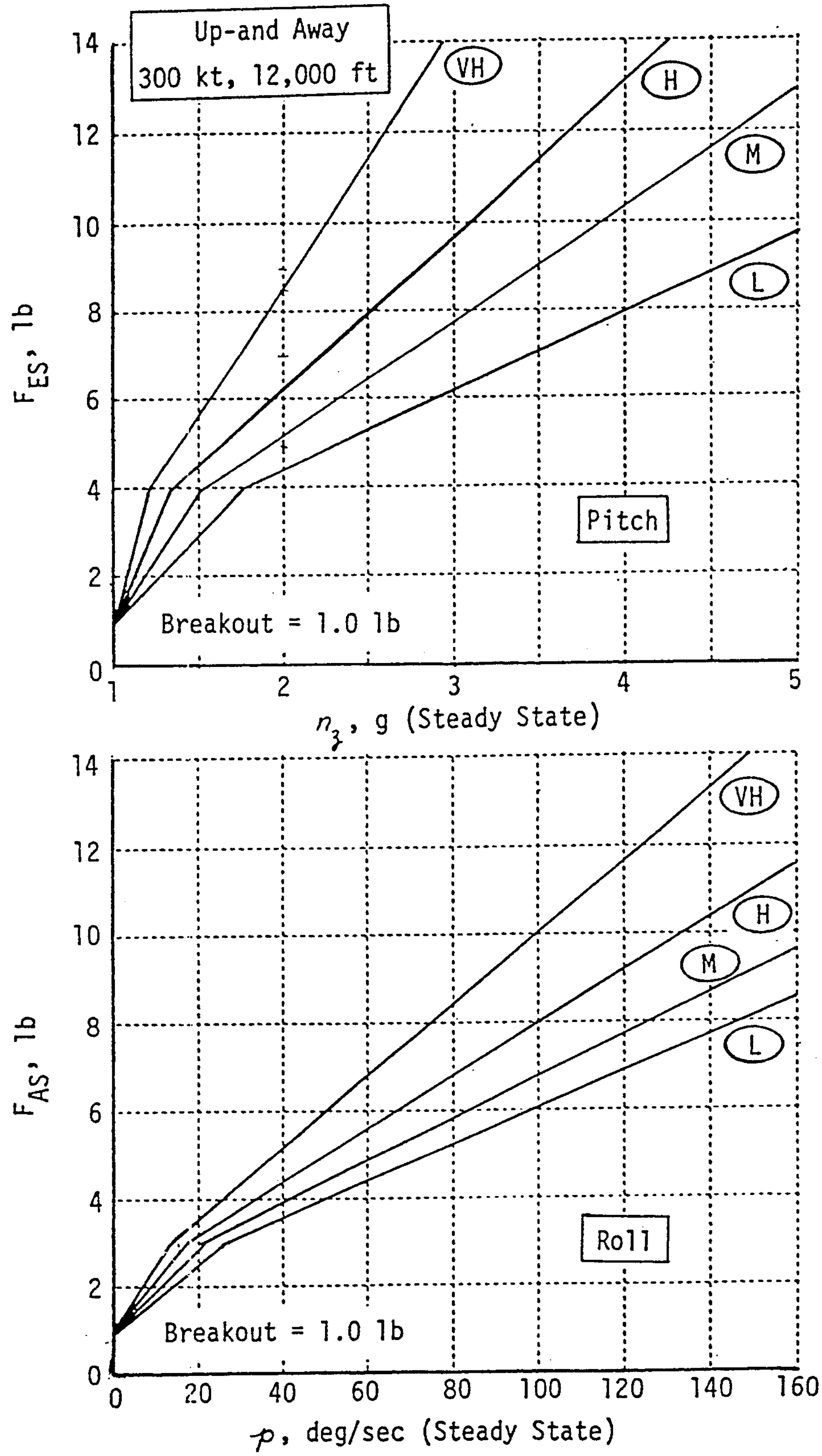
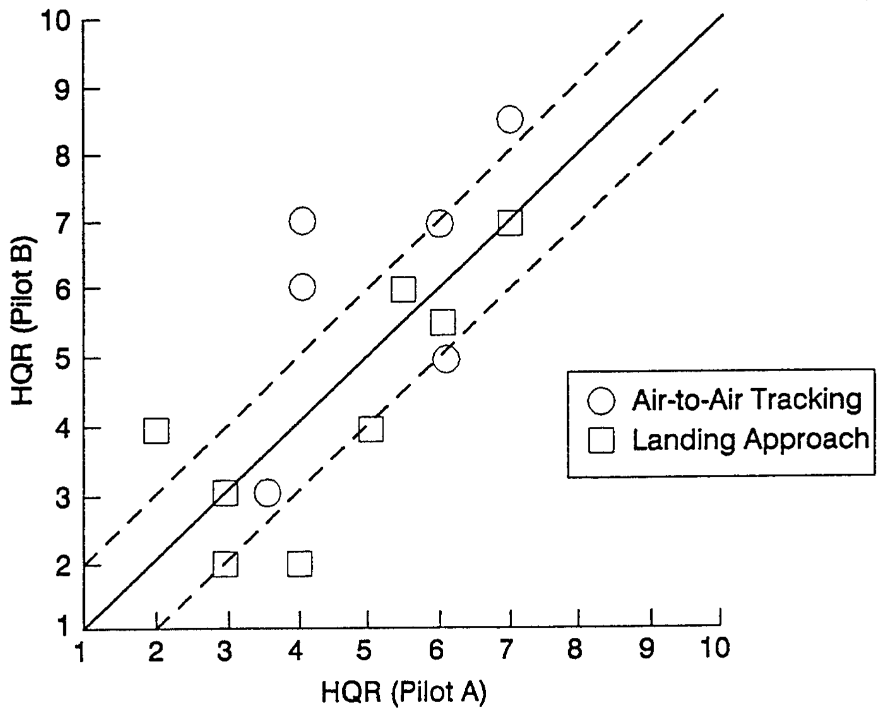
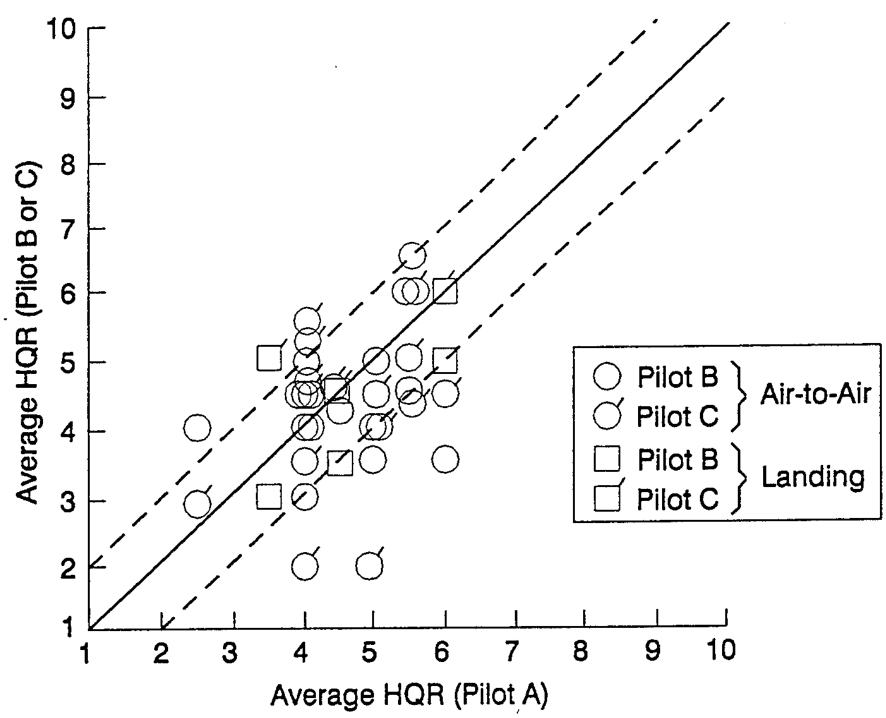


Figure D-7. Control Force-Response Gains, Up-and-Away (Flight Phase Category A) (from Ref. D-16)

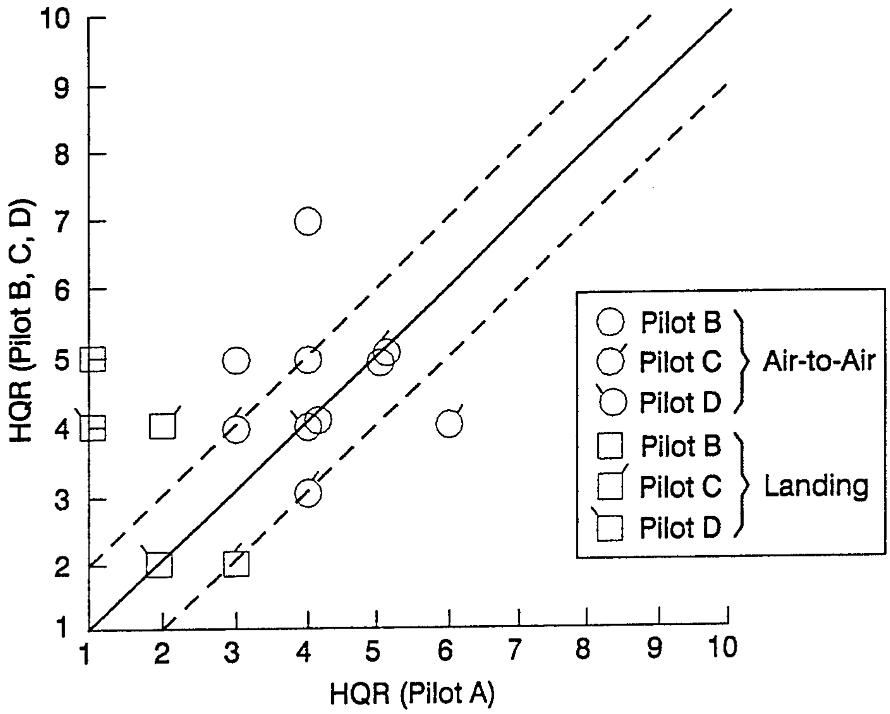


a) Reference D-16

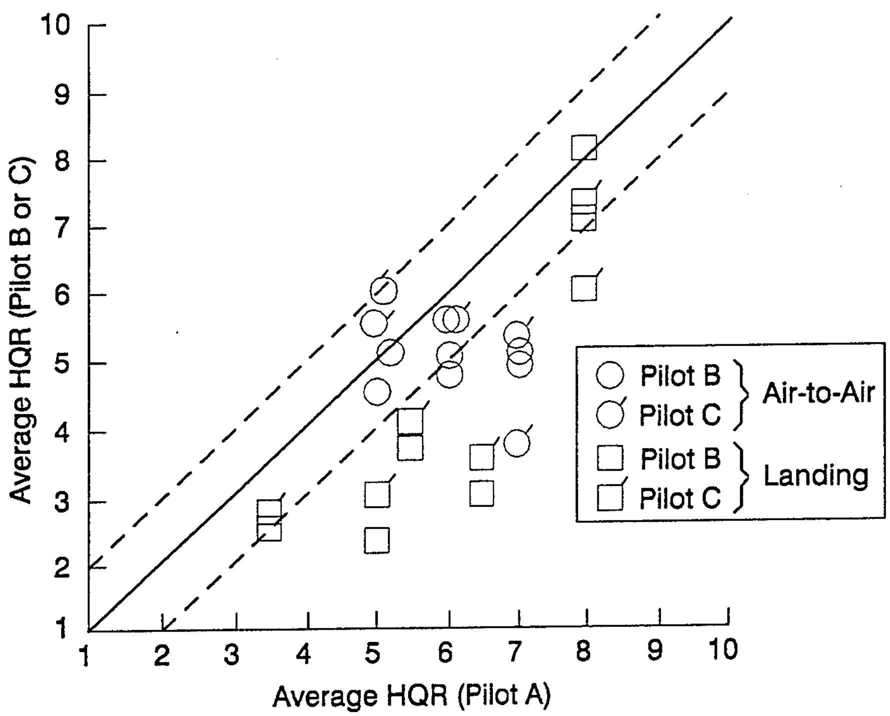


b) Reference D-2 (Appendix B)

Figure D-8. Interpilot Rating Comparisons

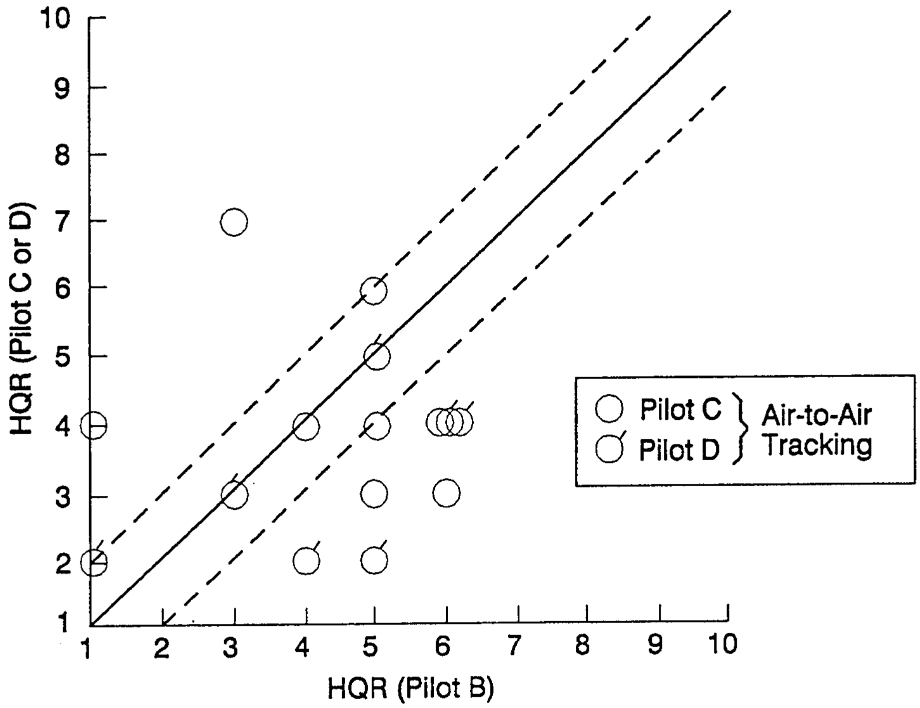


c) Reference D-2 (Appendix C)

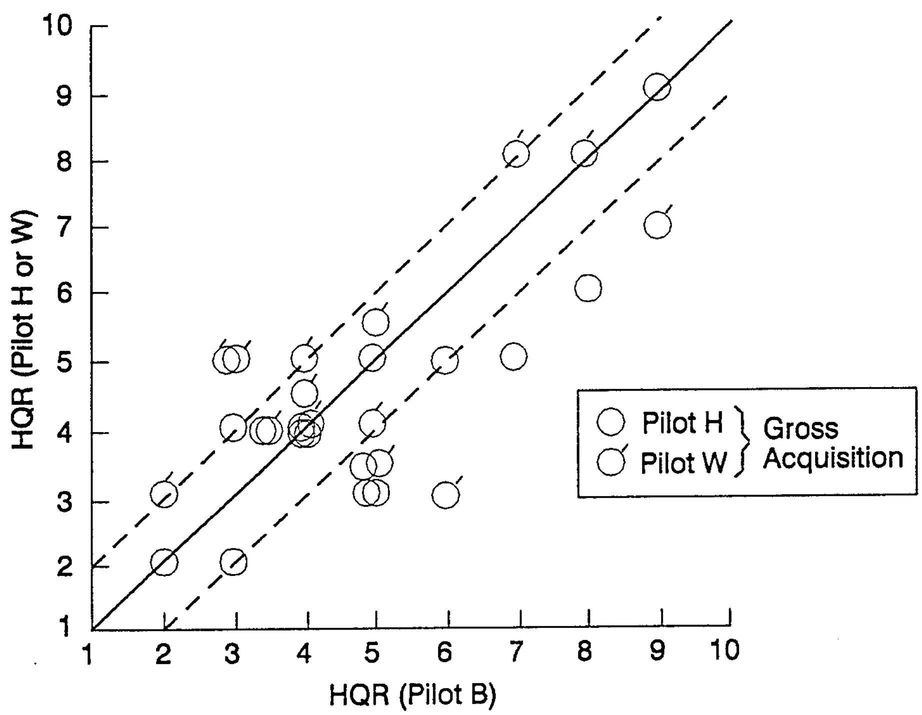


d) Reference D-2 (Appendix D)

Figure D-8. Interpilot Rating Comparisons (continued)

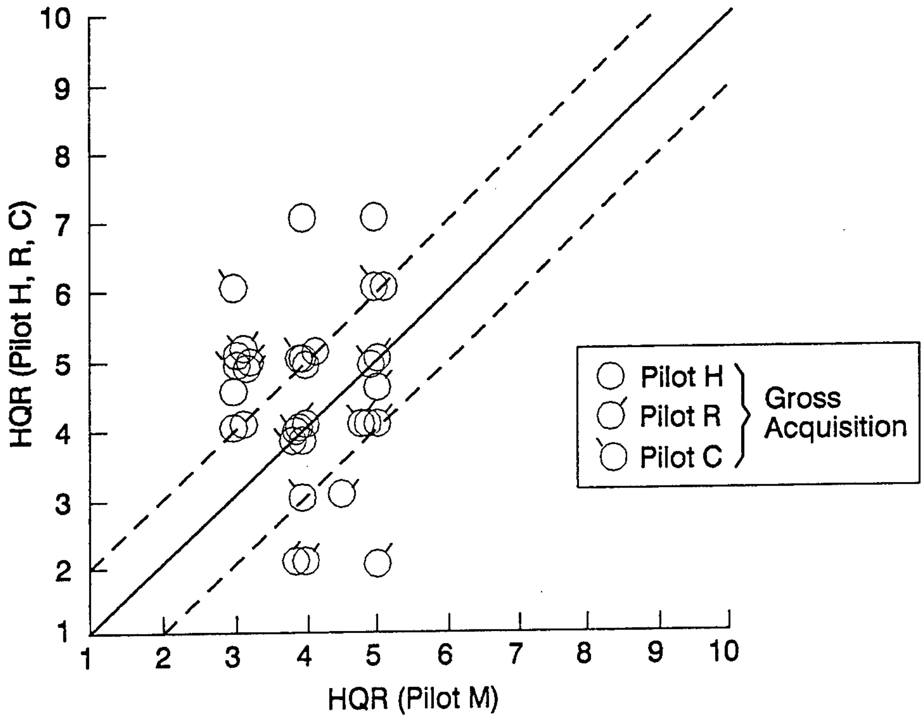


e) Reference D-2 (Appendix E)

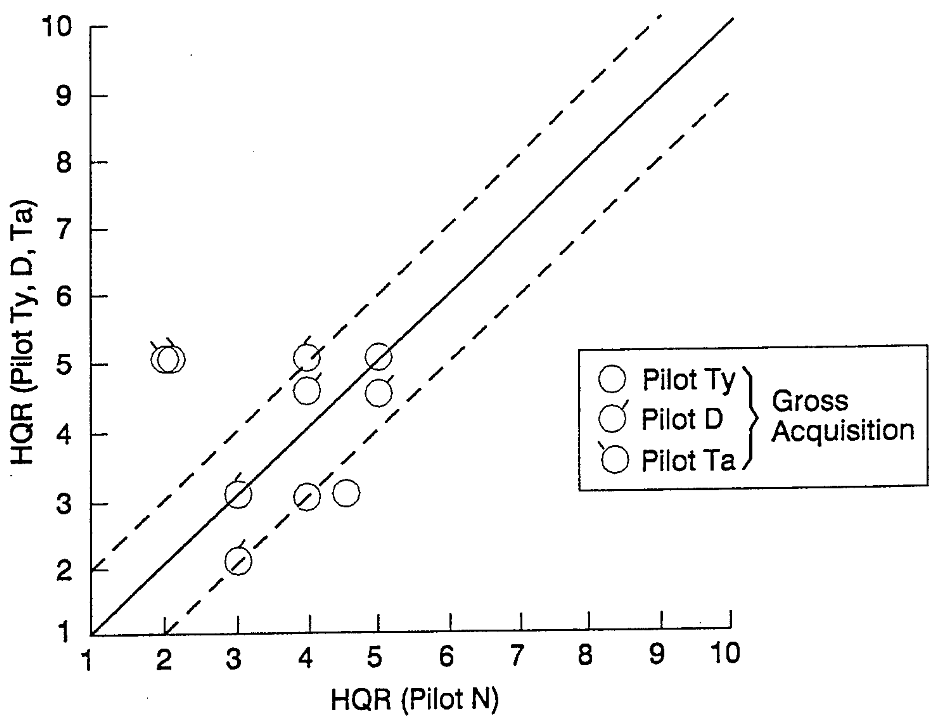


f) Reference D-22

Figure D-8. Interpilot Rating Comparisons (continued)



g) Reference D-25



h) Reference D-24

Figure D-8. Interpilot Rating Comparisons (concluded)

ratings trends for any of the sidestick experiments. As a result, they show a summary of data from different tasks and pilots on each plot. For example, Fig. D-8b includes the ratings comparisons for both Pilots A and B, and A and C, but not for Pilots B and C. The following observations can be made from Fig. D-8:

- For most of the experiments, the pilot ratings vary over a very small range, generally between about 3 and 6 (e.g., parts b, c, e, g, and h of Fig. D-8). This makes it difficult to discern between good and bad handling qualities characteristics. This is even more apparent on the actual data plots, discussed below.

- Interpilot rating scatter is large for most of these experiments as well. The two studies with the greatest range of ratings (Figs. D-8a and D-8f) show the smallest scatter. This scatter is probably due in part to the lack of experience of TPS students (all except Ref. D-16, Fig. D-8a) in assigning ratings, and to the lack of well-defined maneuvers. For the Ref. D-16 Calspan study and all TPS studies documented in Ref. D-2, no mention is made of desired and adequate performance limits for any of the tasks. Without proper definition of performance bounds it is left up to the individual pilot to decide what constitutes an acceptable level of performance.

- There is a shortage of landing data, and the ratings for landings also exhibit scatter. Again, there is no evidence of a defined performance level, and in those experiments where landings were evaluated, the landing task usually consisted of ILS tracking or visual approach to a straight-in landing. The now-standard offset landing was not included (for the TPS study documented in Appendix D of Ref. D-2, it is stated that "if two landings were performed,... the second was offset from centerline," but some evaluations consisted of only one landing).

Despite all of these apparent detractions, the TPS and Calspan data still represent the only documented sidestick pilot rating data for fighter aircraft. These data can be compared to centerstick requirements from MIL-STD-1797A to determine applicability.

- <u>Air-to-Air Tracking (Category A) Tasks</u>

Plots of deflection/force vs. force/response gradients are shown in Figs. D-9 through D-12 for air-to-air tracking tasks. Each figure shows both pitch and roll data; average pilot ratings are indicated on each part of the figures. The MIL-STD-1797A limits on stick deflection/force gradient for centersticks are 0.4 deg/lb to 1.0 deg/lb (Paragraph 4.2.8.4, Appendix A of Ref. D-1). These limits are given as absolutes, i.e., there are no Levels stated. Therefore, it must be assumed that values outside the limits will be worse than Level 2, at least. Pitch control force per g limits are given as functions of n/α and limit load factor, n_L, in Paragraph 4.2.8.1 of Ref. D-1. These limits are compared with the pitch-axis data in Figs. D-9 through D-12; it has been assumed that these data are for a fighter aircraft with a limit load factor of 7 g. For roll, no limits on deflection/force gradient are stated in MIL-STD-1797A; roll response is stated in terms of degrees of bank angle in one second per pound of stick force (Appendix A Paragraph 4.5.9.3, Ref D-1).

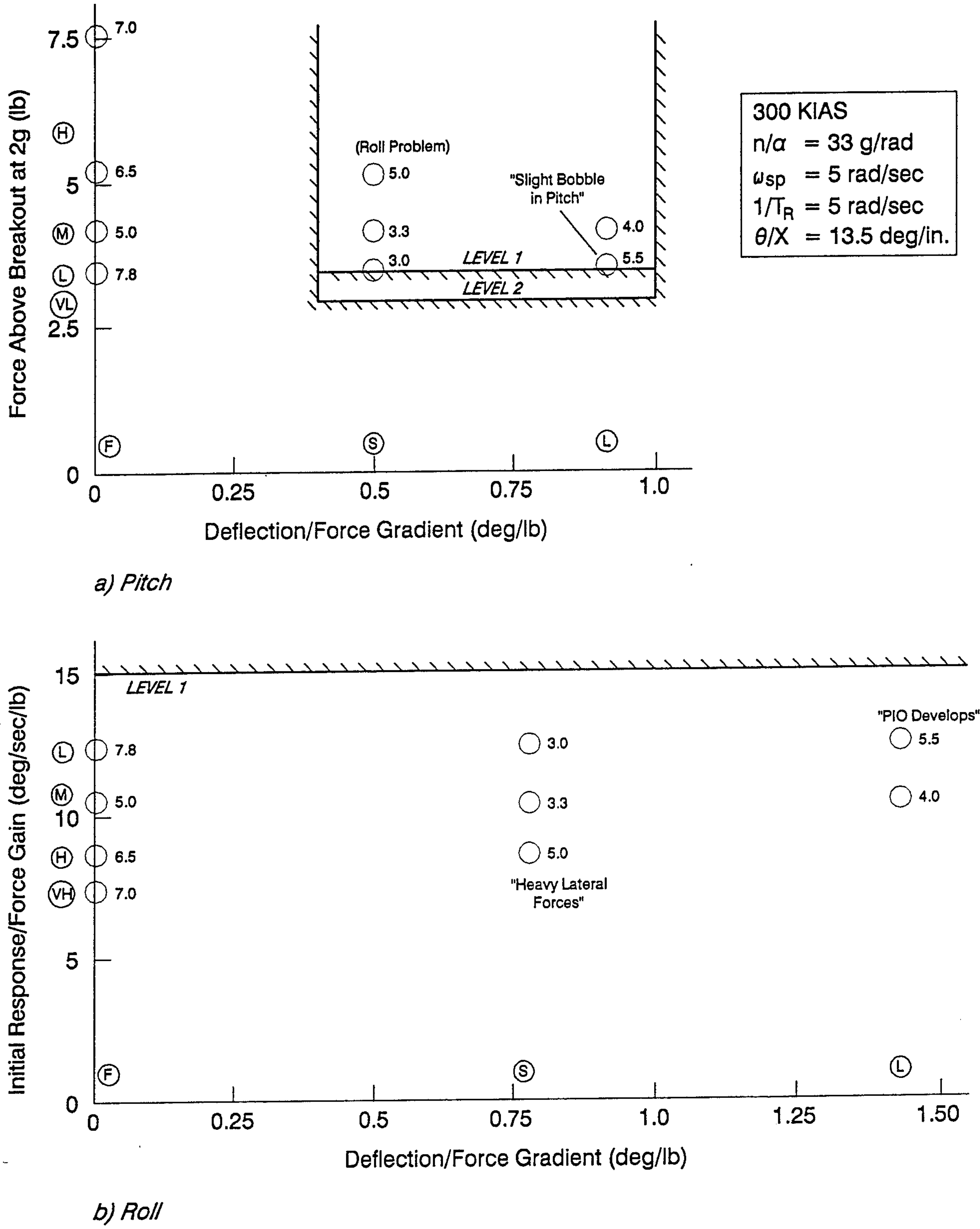


Figure D-9. Class IV, Category A (Air-to-Air Tracking), Ref. D-16

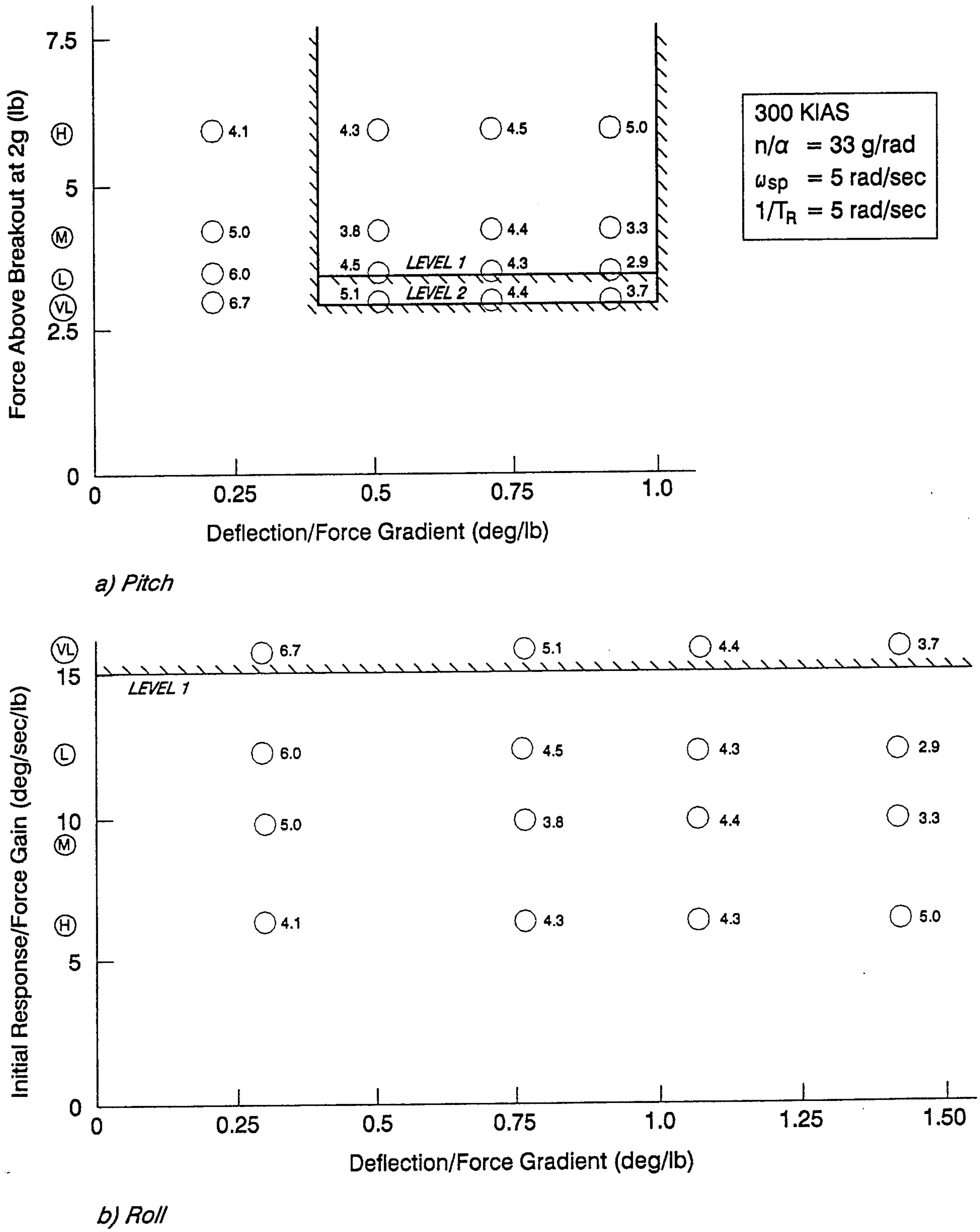


Figure D-10. Class IV, Category A (Air-to-Air Tracking),
Ref. D-2 (Appendix B)

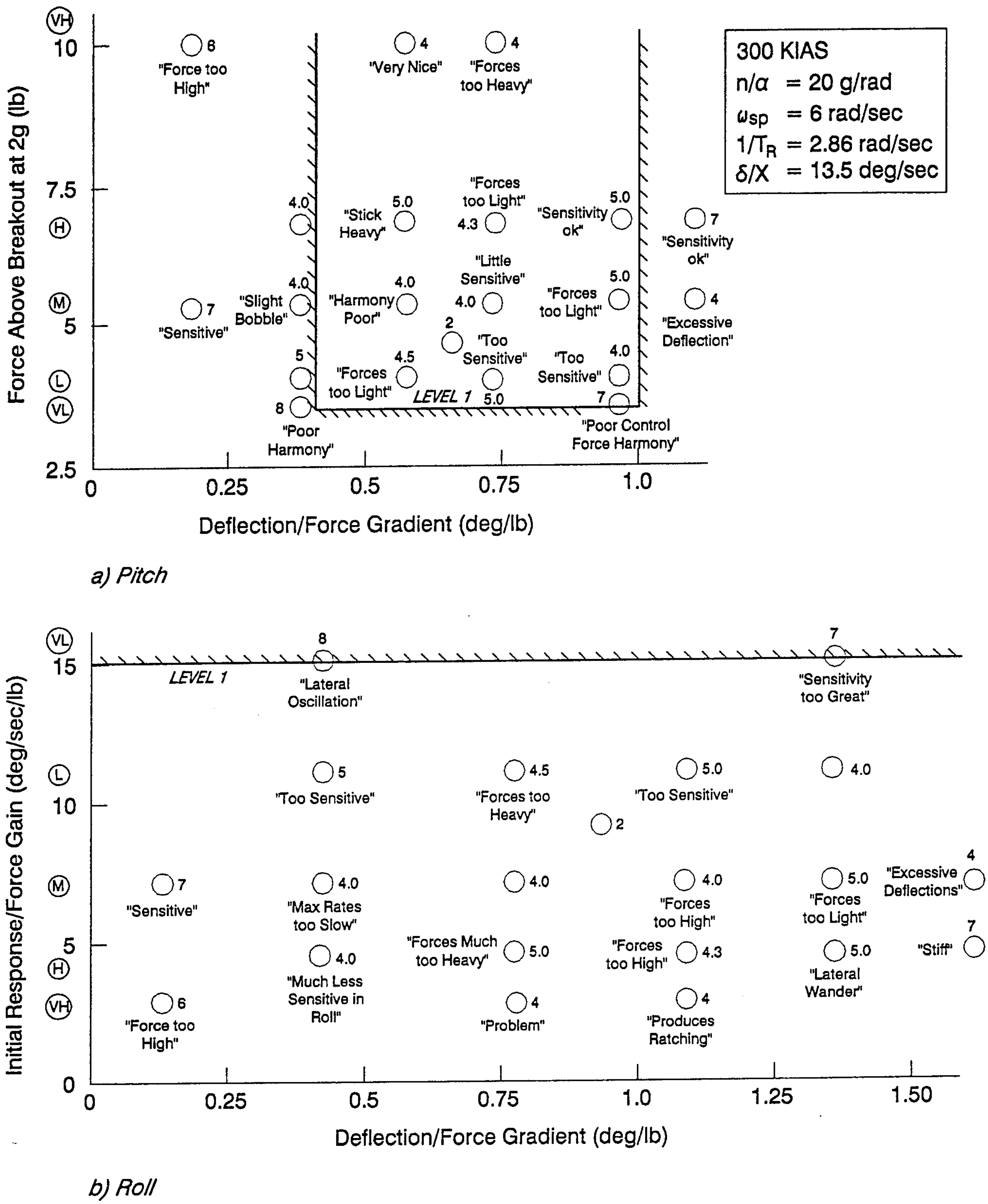
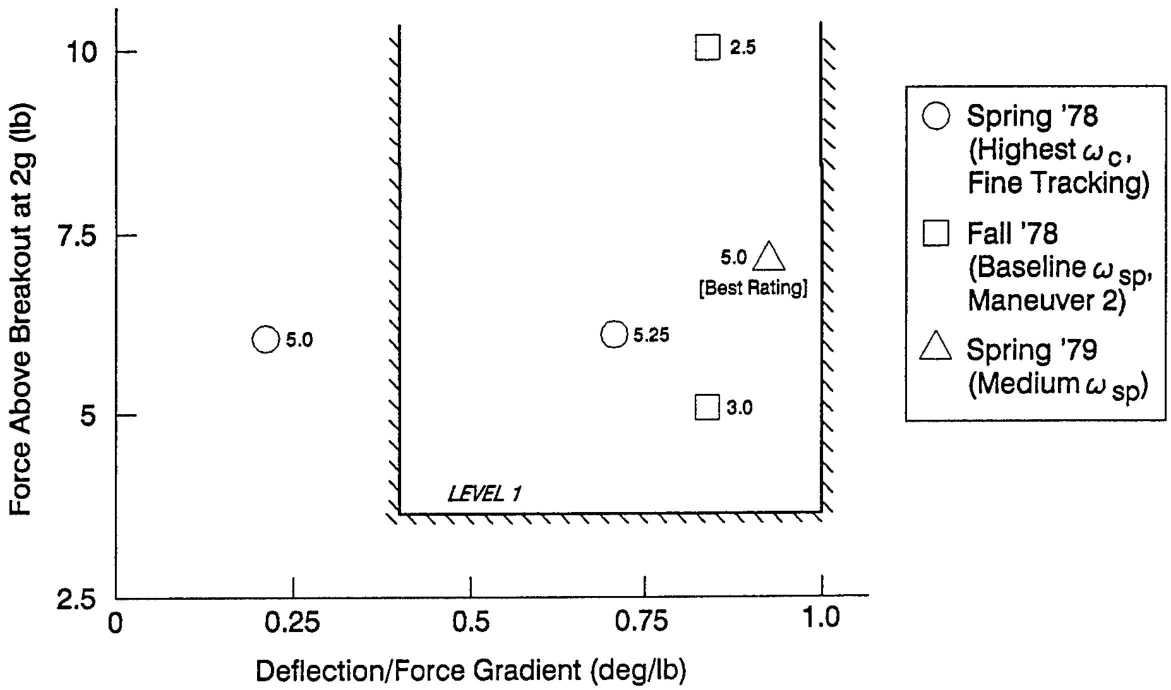
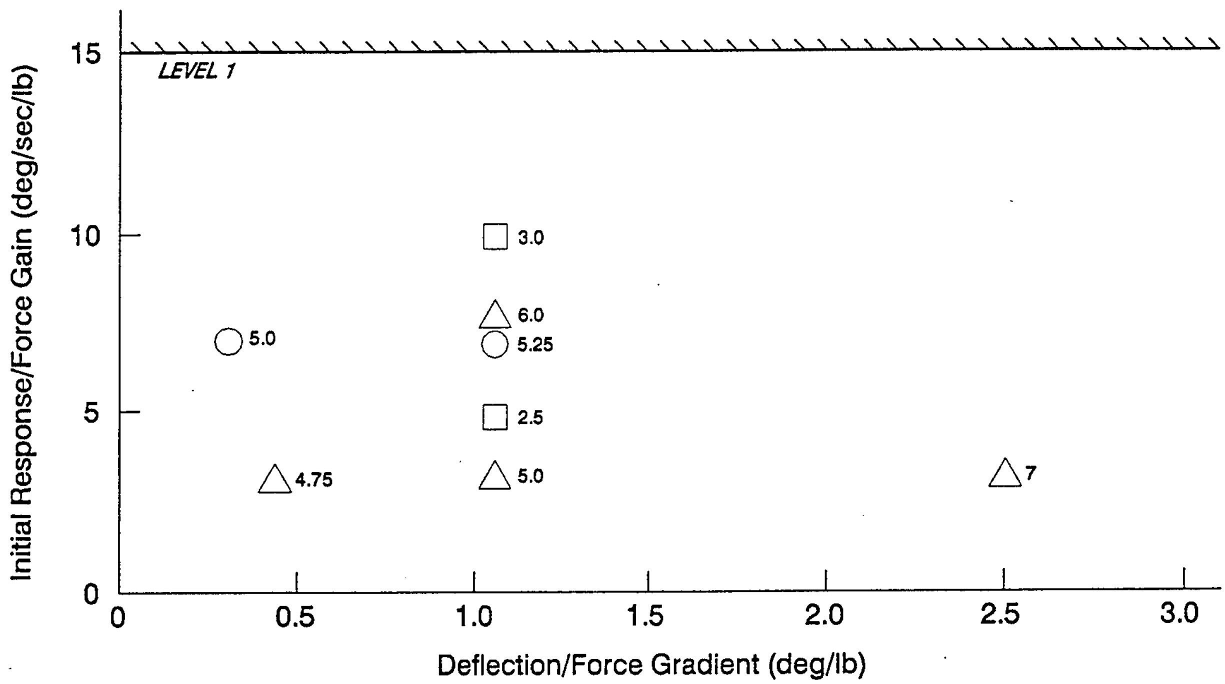


Figure D-11. Class IV, Category A (Air-to-Air Tracking), Ref. D-2 (Appendix C)



a) Pitch



b) Roll

Figure D-12. Class IV, Category A (Tracking), Ref. D-2 (Appendices D, E, F)

This is not identical to roll steady-state response/force gain, but it is sufficiently close for all of the experiments reviewed here since the roll mode inverse time constant, $1/T_R$, was relatively large (2 rad/sec or greater).

A general observation, in concurrence with the interpilot rating data of Fig. D-7, is that there are few Level 1 average HQRs in Figs. D-9 through D-12. Rating trends show some support for the pitch control force per g Level 1 limit of 3.5 lb/g. The few pitch cases below Level 1 (Fig. D-10a) suggest that the Level 2 limit of 3 lb/g is too restrictive, but there are no data to determine what the lower limit should be.

The limits on pitch deflection/force gradient appear to be too stringent for Level 2, but too lenient for Level 1 handling qualities. For example, ratings in Fig. D-10a support a limit closer to 0.5 deg/lb for Level 1 and below 0.2 deg/lb for Level 2. This is further supported by the Fig. D-9a ratings, where a fixed stick received Level 2 average ratings. Based on these figures, recommended sidestick pitch deflection/force gradient limits are 0.5 deg/lb (force/deflection gradient of 2.0 lb/deg) for Level 1 and 0.2 deg/lb (5.0 lb/deg) for Level 2; at the other end, 1 deg/lb is probably reasonable for Level 1, but a Level 2 limit cannot be determined.

In roll, the data of Figs. D-9 through D-12 suggest that 15° in one sec per lb is a reasonable Level 1 upper limit on sensitivity. In addition, a Level 1 lower limit should be set around 5° in one sec per lb. As far as deflection/force gradients in roll, the lower limits given above for pitch (0.5 deg/lb for Level 1 and 0.2 deg/lb for Level 2) are supported, while the data in Fig. D-10b indicate that very large deflection/force gradients are acceptable in roll. An upper Level 1 limit of 1.5 deg/lb may be reasonable.

- Nonprecision Landing (Category C)

Since the landing evaluations in the sidestick experiments did not include precise touchdown requirements or offsets on short final, the landings are representative of nonprecision landings, defined, in the newly proposed set of Mission Task Elements (MTEs), as a Category C task.

Landing data are shown in Figs. D-13 through D-15. There are no limits in MIL-STD-1797A for centerstick deflection/force gradients in landing. The Category A limits are shown in the pitch plots of Figs. D-13 through D-15. The Level 1 upper limit on stick force per g, 28 lb/g, is clearly not appropriate based on the ratings in Fig. D-15a. Level 1 ratings were obtained for gradients up to 50 lb/g, and a more reasonable Level 1 limit might be the current Level 2 value of 42.5 lb/g (Appendix A of Ref. D-1, Paragraph 4.2.8.1). The requirements on control force per g should be separated more definitively between Category C and low-speed Category A operations. In terms of deflection/force limits for landing, the lower limit of 0.4 deg/lb is much too restrictive: Level 1 ratings were obtained for a fixed stick in the Ref. D-16 study (Fig. D-13a) and for 0.2 deg/lb in one of the TPS studies (Fig. D-14a). The revised limits given above for Category A operations should be adopted for Category C as well.

In roll, the Level 1 sensitivity limit of 7.5° in one sec per lb is too low. This should be increased to about 10 based on the sidestick data. A Level 2 limit cannot be determined. Based on the data of fig. D-15b, a Level 1 Lower limit of about 4° in one sec per lb should be established.

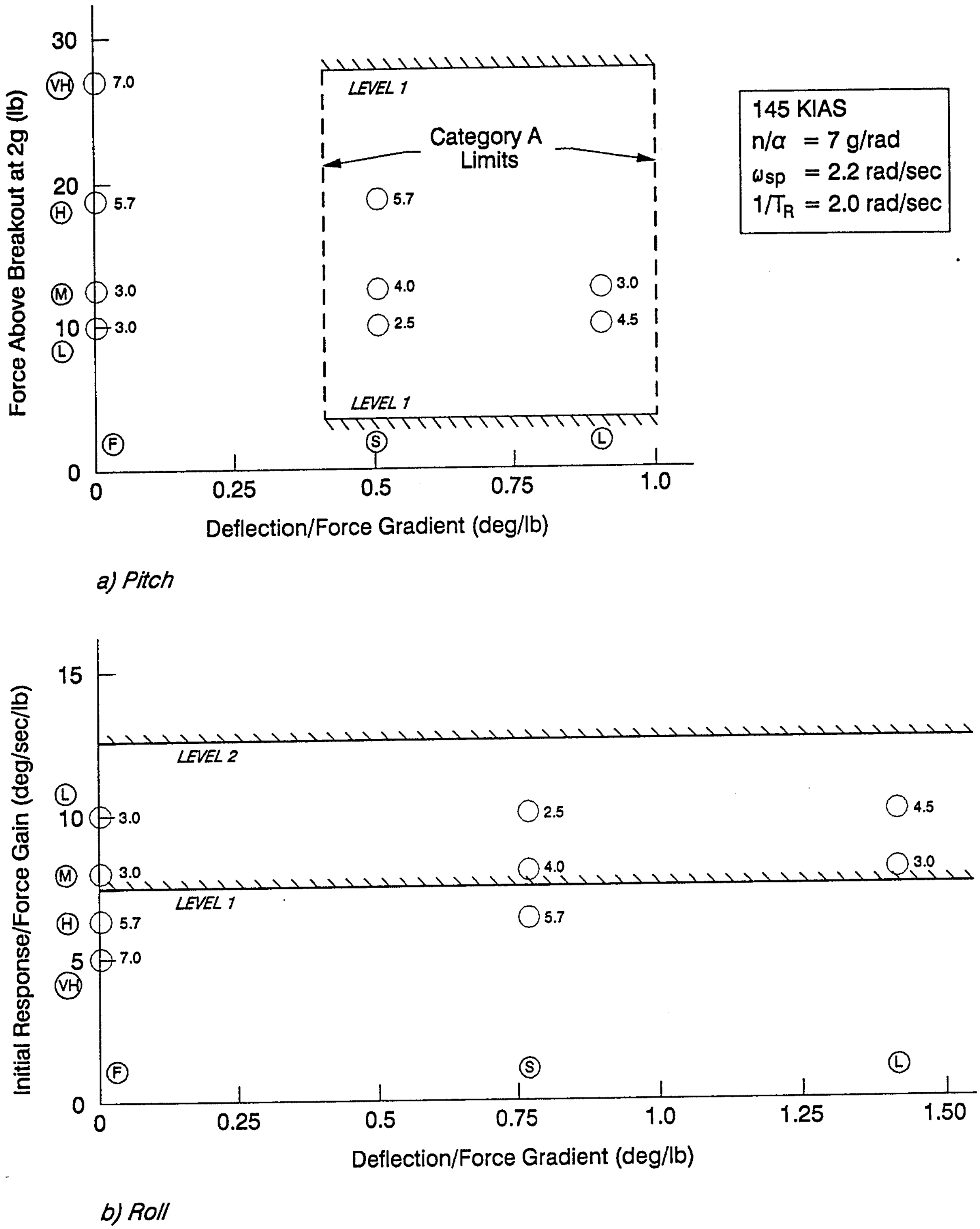


Figure D-13. Class IV, Category C (Landing), Ref. D-16

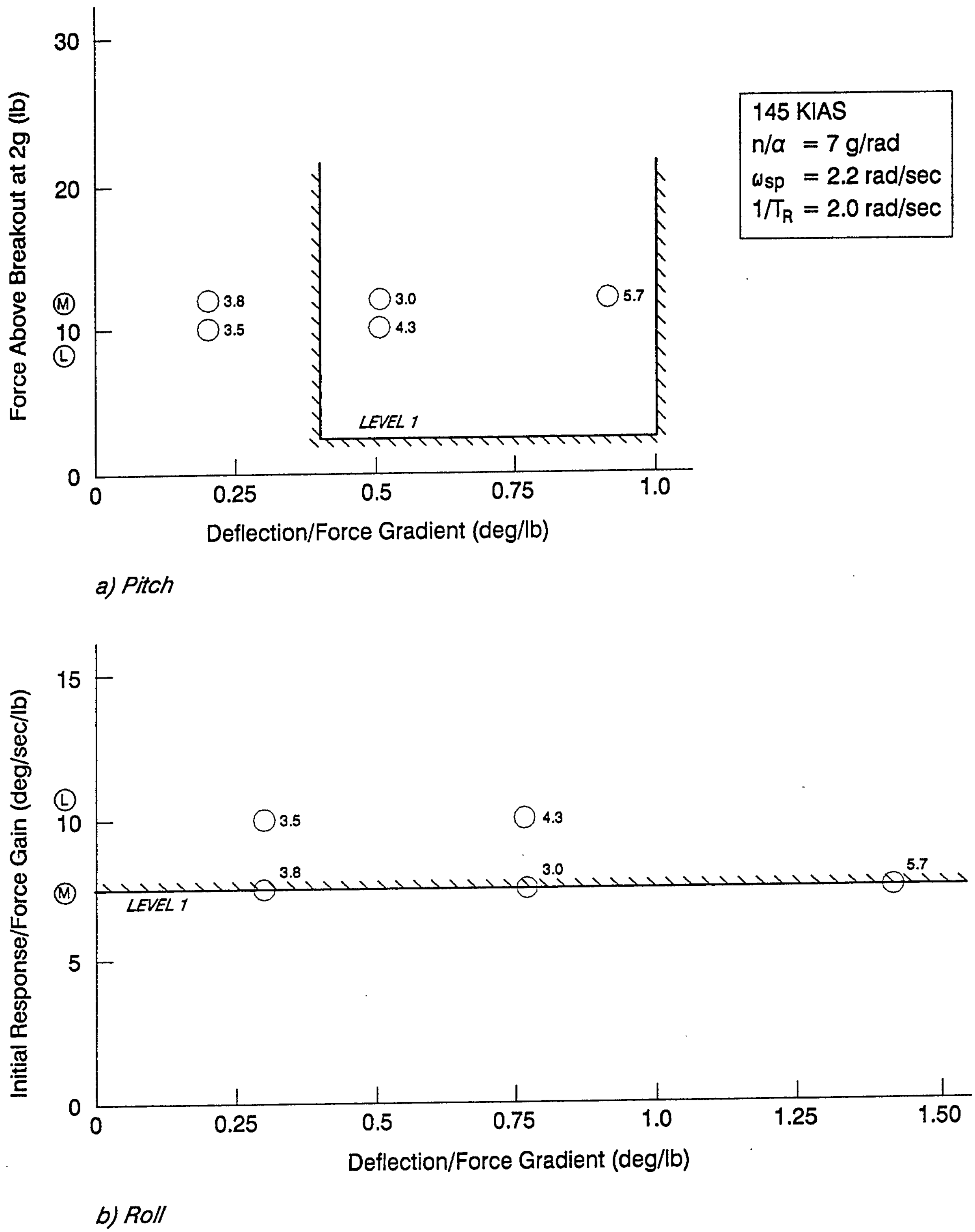


Figure D-14. Class IV, Category C (Landing), Ref. D-2 (Appendix B)

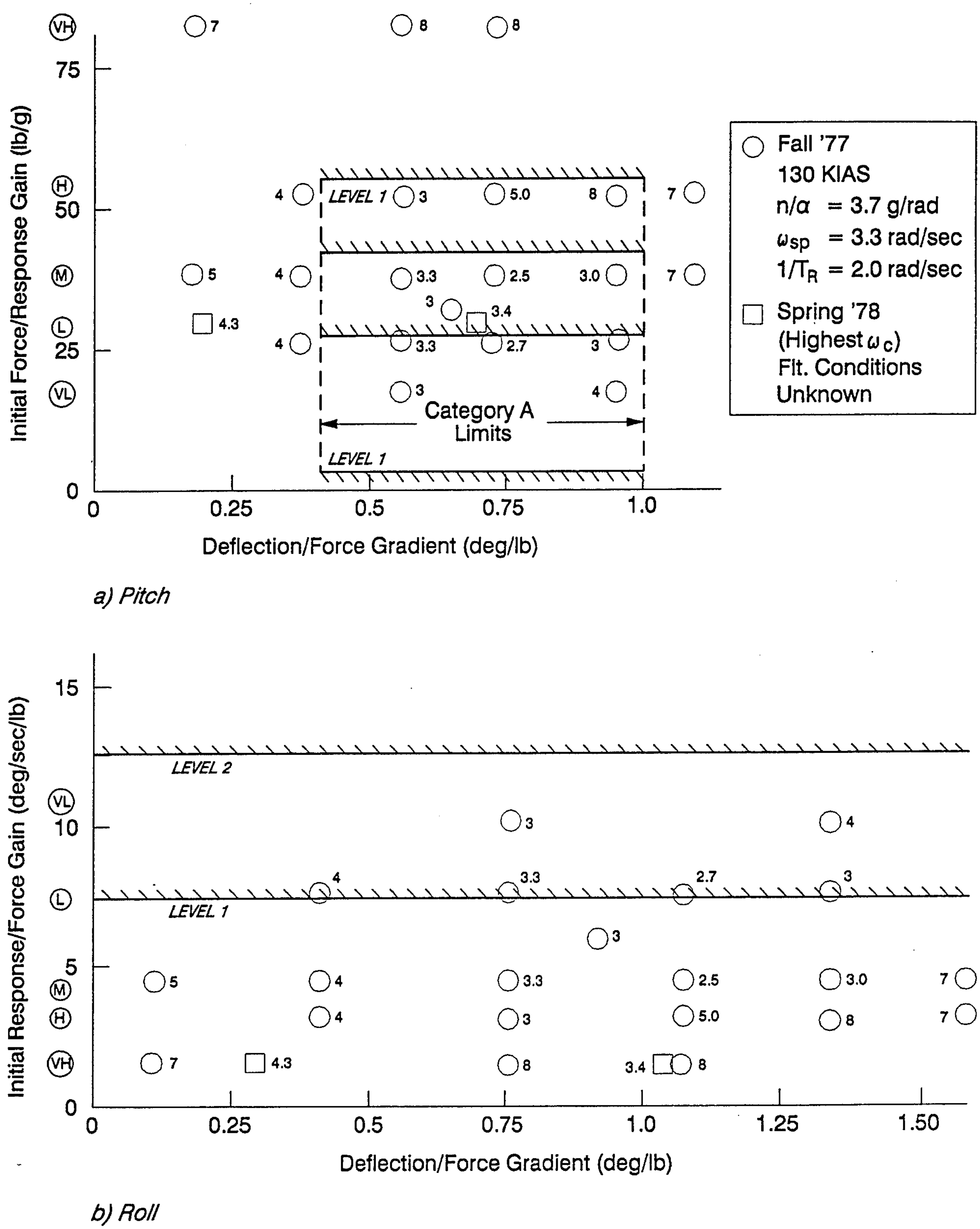


Figure D-15. Class IV, Category C (Landing), Ref. D-2 (Appendices C and D)

d. Class III (Transport) Data

The Ref. D-17 simulation, conducted at NASA Ames Research Center, investigated many of the issues raised by the use of sidestick controllers. Control sensitivity was evaluated over a range of values in pitch and roll. The facility was a fixed-base simulator. Obviously, great care must be taken in attempting to define response characteristics from any ground simulations, especially fixed-base, since it is common for the pilots to select response gains that are much higher than will ever be accepted in flight. The simulation task in Ref. D-17, however, was IMC maneuvering, where the lack of motion cues would not be as significant. Figure D-16 shows the average ratings from the Ref. D-17 study. Unlike the fighter experiments reviewed above, the pilots in the Ref. D-17 simulation separately rated pitch and roll control variations.

Figure D-16a is a crossplot of deflection/force gradient vs. force/response gain for pitch. The average HQRs show a preference for the lowest deflection/force gradient evaluated, 0.4 deg/lb, and for the medium value of force/response gain, 13.5 lb/g. Since lower values of deflection/force gradient were not considered it is impossible to determine whether values below 0.4 deg/lb would be better or worse. MIL-STD-1797A requires between 0.4 and 1 deg/lb. This encompasses the range of values in Fig. D-16a, suggesting it is reasonable for transports as well. The A320's stick lies within this range in Fig. D-16a (Ref. D-15).

The roll deflection/force gradients evaluated in Ref. D-17 varied from 0.6 to 1.2 deg/lb, with response/force gains from 1.25 to 3.33 deg/sec/lb (Fig. D-16b). Again, pilot ratings are better for the lower values of deflection/force gradient and medium response/force gain. It appears from these data that gradients in excess of 1 deg/lb may still be acceptable in roll; in fact, as Fig. D-16b shows, the A320, Space Shuttle, and experimental C-141 FBW aircraft (Ref. D-10), all have much larger deflection/force gradients. The existence of larger gradients does not, of course, guarantee that these values are good; in the case of the C-141 FBW, however, Ref. D-10 reports that 5 deg/lb was the "preferred" gradient. Based on these data, it would seem that values of roll deflection/force gradient as high as 5 or 6 deg/lb may be acceptable, at least in roll. But the response characteristics must be considered as well: very high deflection per force, with very low roll rate per force, means that either the maximum roll rate capability will be limited or the maximum deflection of the stick will be very large. Consider, for example, the values for the C-141 FBW in Fig. D-16b: with a response/force gain of 3.45 deg/sec/lb, a roll rate command of 25 deg/sec requires a 7.25-lb input (above breakout). With a 5 deg/lb gradient, the resulting stick deflection is 36.25° — much too large to be comfortable to the pilot. If a maximum roll rate command of 25 deg/sec and maximum stick deflection of 20° are considered, a gain of 3.45 deg/sec/lb dictates a deflection/force gradient of

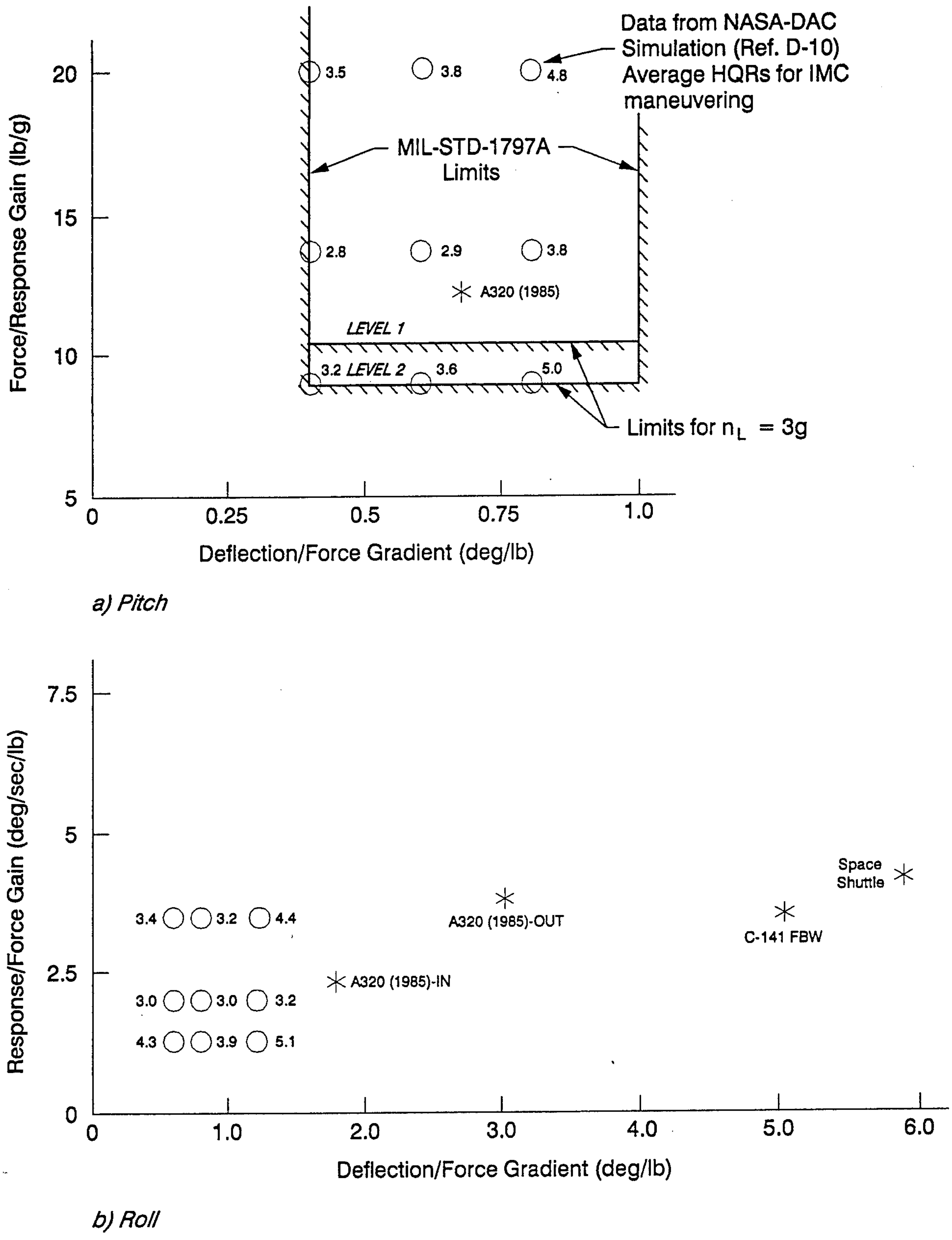


Figure D-16. Force/Deflection and Force/Response Gradients for Transports

20/7.25 = 2.76 deg/lb. Therefore, it seems reasonable to limit the upper range of deflection/force gradients in roll to about 3 deg/lb or less.

e. Asymmetric Response Characteristics

The human hand can apply more lateral force inboard (i.e., to the left for a right-handed stick) than outboard. As a result, the design of symmetric control forces and response characteristics may be a compromise between the two directions. A solution to this asymmetry is to make either the force/deflection characteristics or the force/response gains asymmetric. Both methods have been applied. An NT-33A flight evaluation of different roll response gains for left vs. right rolls was conducted by students of the USAF Test Pilot School (Ref. D-23). The gain for left rolls (inboard for the right-hand stick) was fixed at a preferred value of 3.3 deg/sec/lb, while the gain for right rolls was increased up to a factor of three above the left-roll value. Average HQRs are shown on a crossplot of force/response gain for right rolls vs. roll mode time constant, T_R, in Fig. D-17, for the gross acquisition task. Both gross acquisition and fine tracking task were performed; the former is considered more relevant for evaluation of response gains, since it requires larger initial control inputs.

The pilots in the Ref. D-23 experiment noted problems with lateral-directional control during rudder-free maneuvering, so the tasks were performed both with and without use of rudders. Both sets of ratings are noted on Fig. D-17. There are no significant changes in the average pilot ratings for right-roll-command force/response gains of 1.5 and 3 times the left-roll gain. Pilot comments and performance measures suggested that an asymmetric response was somewhat improved over the symmetric response when the inboard response/force gain was 2/3 of the outboard value (right-roll gain of 5 deg/sec/lb).

The A320 has adopted the second approach to control asymmetry: the inboard deflection/force gradient is about 2/3 that for outboard inputs, resulting in a commensurate change in response/force gains (Fig. D-16b).

Asymmetric force limits and gradients in pitch are quite common for sidesticks, due primarily to the much greater need to apply aft as opposed to forward control inputs. The F-16 uses asymmetric fore/aft force and deflection limits (Fig. D-5) that result in a forward deflection/force gradient that is 1/9th the aft gradient.

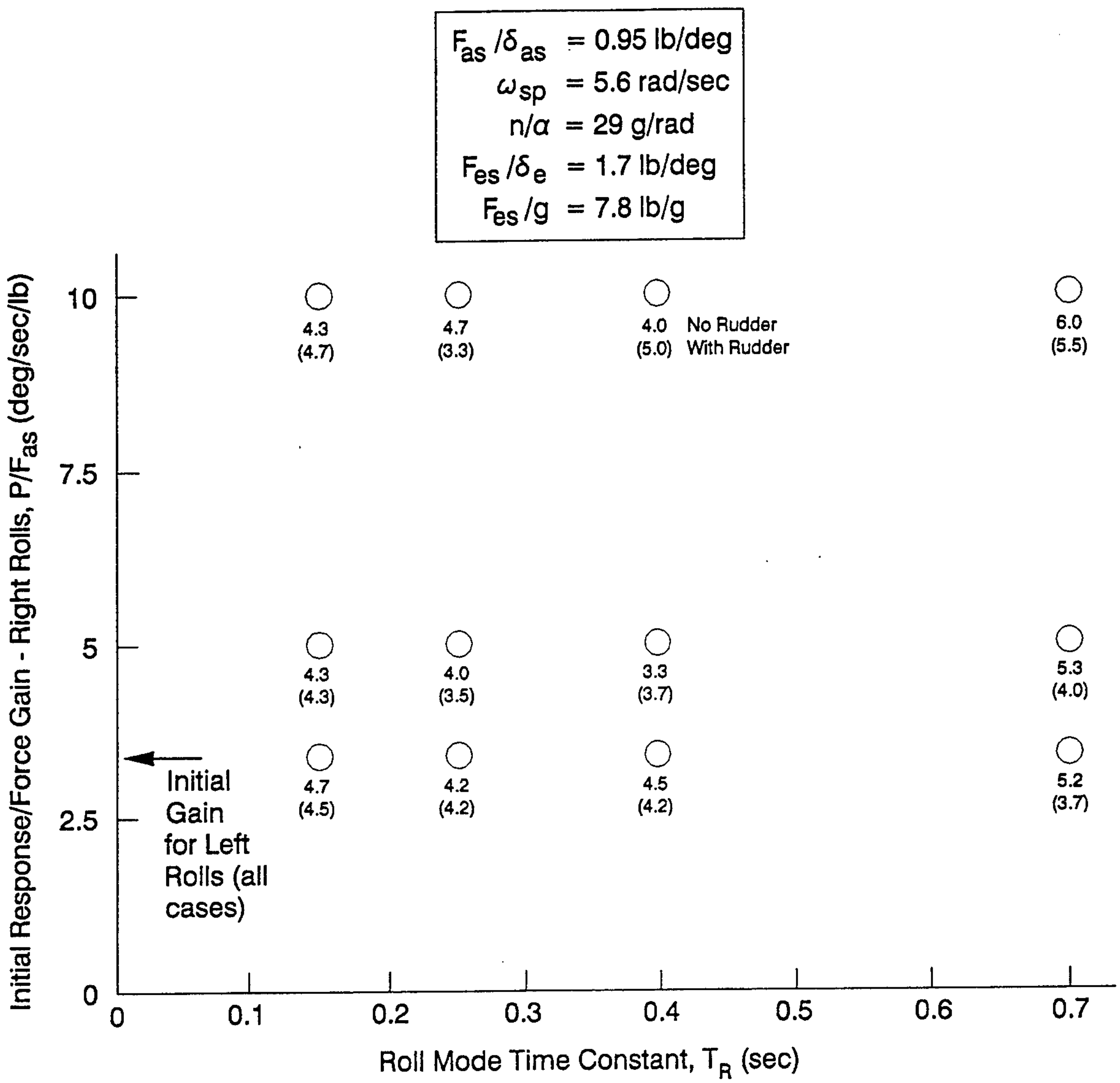


Figure D-17. Pilot Ratings for Asymmetric Roll Response/Force Gain (Ref. D-23), Gross Acquisition Task

3. Interaction with Aircraft Dynamics

Based on the limited sidestick available at the time, the authors of the draft MIL Standard (Ref. D-8) suggested that there is a weak relationship between longitudinal stick force per g and short-period frequency. The applicable data are included in Appendix A of MIL-STD-1797A (Ref. D-1), in Fig. 104 on page 307. This figure has been redrawn for this working paper: several of the data points in the referenced figure are incorrectly plotted; a number of additional data points from the initial references have been added; and other data from the more recent tests (Ref. D-24) have been included. The new figure is shown as Fig. D-18.

Handling qualities Levels from 1797A are included on Fig. D-18 based on n/α = 29 g/rad, which is the reference value for almost all of the experiments. Stick force per g limits shown are for centerstick controllers. Average HQRs are noted for the gross acquisition task from each reference. It can be observed that, in general, there is good agreement with the Level boundaries. Most of the Level 2 ratings in the Level 1 region are from Ref. D-2 (diamond symbols); few configurations in this reference were given Level 1 ratings. The relationship between ω_{sp} and F_s/n reported in 1797A, which was due almost entirely to the Ref. D-2 ratings, is not apparent in Fig. D-18.

Similar data are shown in Fig. D-19 for the landing task. There are data for only two values of ω_{sp}, 2.2 and 3.3 rad/sec, so it is impossible to identify any relationship between short-period frequency and stick force per g. The data of Fig. D-19 were previously presented in Figs. D-14 and D-15, where they provided support for relaxing the upper limits on stick force per g in landing.

Figure D-17 showed a limited amount of rating data for roll gain vs. roll mode time constant. There is some preference for the middle values of T_R, 0.25 and 0.4 sec, and there is only a very slight preference for increased response gain as T_R is reduced (i.e., the best ratings — either with or without rudder — are for T_R = 0.7 sec, p/F_{as} = 3.3 deg/sec/lb; T_R = 0.4, p/F_{as} = 5; and T_R = 0.25, p/F_{as} = 10). This is counter to expectations, since one would expect the pilots to prefer lower sensitivity as the initial short-term response becomes more rapid.

The TPS experiment of Ref. D-24 investigated combinations of short-period frequency and roll mode time constant for both centerstick and sidestick controllers. The resulting average pilot ratings for both gross acquisition and fine tracking are shown in Fig. D-20. For both controllers the best ratings for gross acquisition (and for fine tracking with the centerstick) were given for the following combinations of dynamics: ω_{sp} = 4 rad/sec with T_R = 0.4 sec, and ω_{sp} = 6 rad/sec with T_R = 0.25 sec. This suggests that the pilots preferred some level of response harmony in pitch and roll. Since the stick characteristics

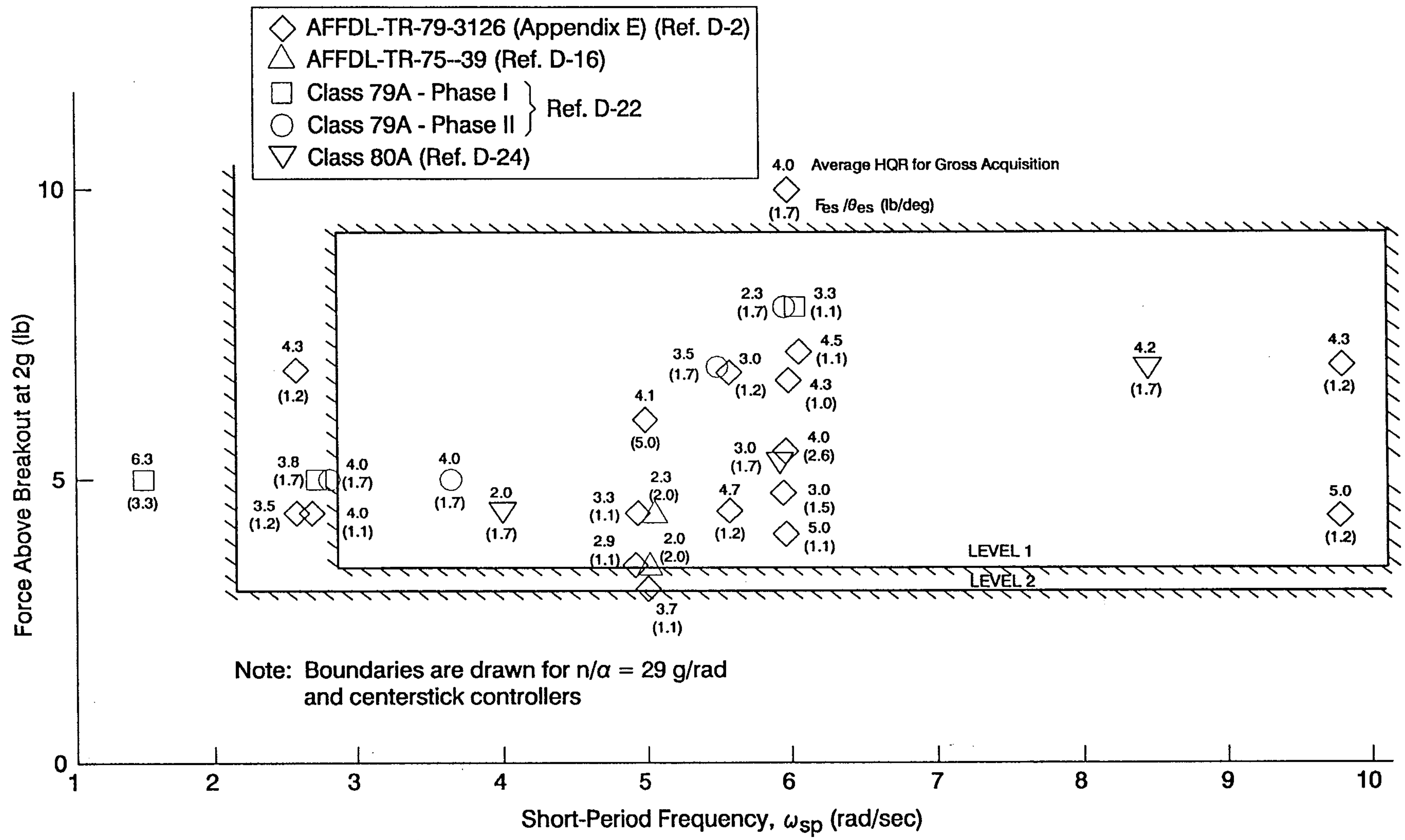


Figure D-18. Short-Period Frequency *vs*. Longitudinal Stick Force per g for Gross Acquisition Tasks ($\zeta_{sp} \doteq 0.7$)

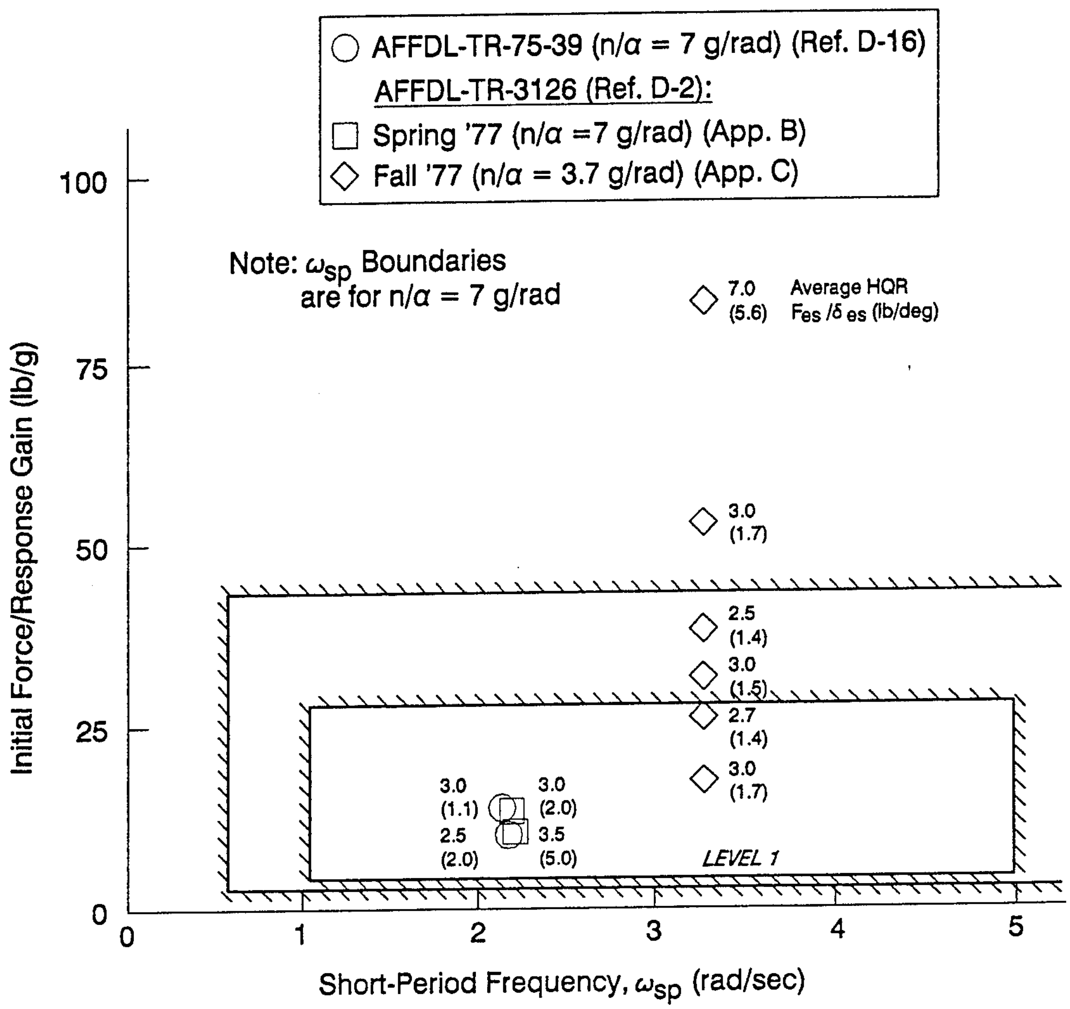
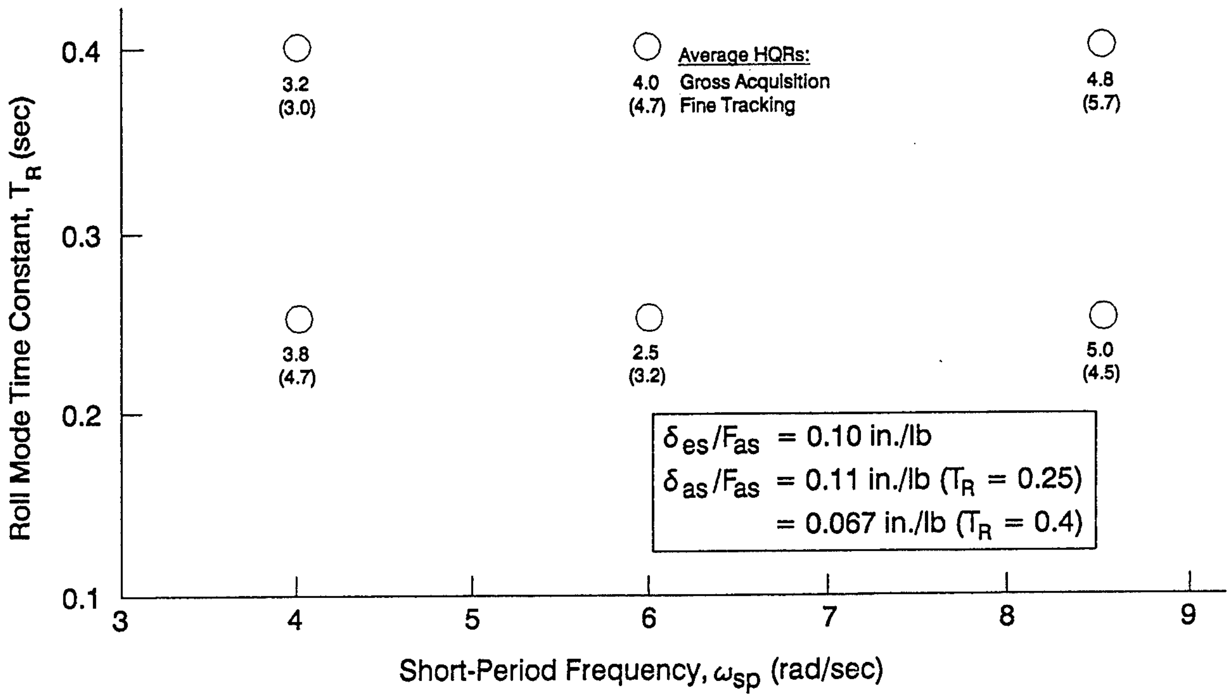
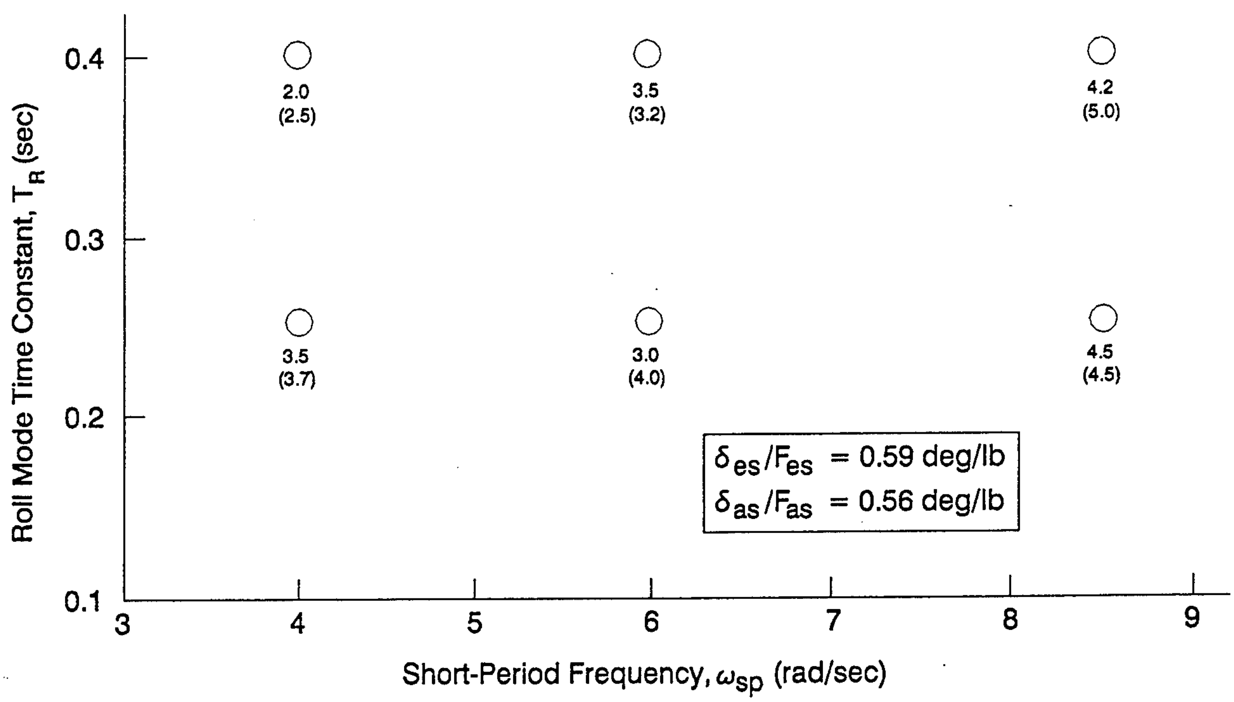


Figure D-19. Short-Period Frequency *vs.* Longitudinal Stick Force per g for Landing ($\zeta_{sp} \doteq 0.7$)



a) Centerstick (no breakout force)



b) Sidestick (1/2 lb pitch and roll breakout)

Figure D-20. Pilot Ratings for Combinations of Short-Period Frequency and Roll Mode Time Constant, Gross Acquisition and Fine Tracking (Ref. D-24)

were held fixed, the data of Fig. D-20 do not give any information on pilot preference for force/response gains as the aircraft dynamics were varied.

G. OPERATIONS IN THE TWO-PILOT COCKPIT

With sidestick controllers, the natural crossfeeding of information between pilots in multi-crew cockpits can be reduced or lost entirely. For example, the sidesticks on the A320 are not mechanically coupled in any way, so motion of one stick does not get reflected in the other stick. As a result, there is a potential for simultaneous pilot inputs, producing increased commands if both sticks are deflected in the same direction, or canceling of commands if they are deflected differentially. To overcome this, the A320 uses a "priority" switch to designate the pilot flying: if the other pilot wishes to take over, he must move his stick in a direction opposite the other stick, with greater than 75 percent of deflection, for several seconds, before control is transferred.

Sidestick control coupling arrangements were investigated in the NASA-Douglas Aircraft Co. simulation of Ref. D-17. The coupling arrangements were: 1) fully coupled; 2) fully uncoupled; 3) uncoupled but with a disconnect button on each stick (depressing the button removed the other stick from the loop; in the event both were depressed simultaneously, the captain's stick prevailed); and 4) uncoupled with priority logic similar to the A320's. The simulated scenario consisted of the pilot flying a final descent, an ILS approach, and a touch-and-go, with an instructor pilot in the right seat. During these maneuvers the instructor pilot would attempt to take over control of the aircraft without informing the pilot.

Not surprisingly, the fully coupled controls were considered best: both pilots had immediate feedback of the other's actions and the response time of the pilot flying was shortest for this arrangement. The uncoupled control arrangement with a disconnect button was second best, though response times were relatively high. The uncoupled controls with priority logic were not considered desirable, "due to the inability of the pilots to retain control of the system in a conflicting situation." In more than 50 percent of the test maneuvers the override attempt was not successfully completed with the priority logic, while all other configurations showed a much greater completion percentage.

H. PROPOSED REVISIONS TO CONTROL FORCE AND CONTROL POWER REQUIREMENTS IN MIL-STD-1797A

The results of this review of sidestick data are summarized in Table D-1 as proposed revisions to the relevant requirements contained in Appendix A of MIL-STD-1797A. Most of the supporting data for the proposed requirements are contained in Section F of this Appendix.

TABLE D-1. PROPOSED REVISIONS TO MIL-STD-1797A REQUIREMENTS FOR SIDESTICKS

MIL-STD-1797A, App. A Paragraph (Page No.)	Subject	Current Requirements	Proposed New Requirements
4.2.8.1 (p.302)	Pitch axis control forces—steady-state control force per g	None	$(F_s/n)_{min}$ = current centerstick limits $(F_s/n)_{max}$: Level 1 = current Level 2 at low n/α, current Level 1 at high n/α Level 2 = current Level 3
4.2.8.4 (p.327)	Pitch axis control forces—control force vs. control deflection	1-2.5 lb/deg (0.4-1 deg/lb)	Class III: Level 1 = 1.25-2.5 lb/deg (0.4-0.8 deg/lb) Level 2 = 1-5 lb/deg (0.2-1 deg/lb) Level 3 max = ∞ (0 deg/lb) Class IV: Level 1 = 1-2 lb/deg (0.5-1 deg/lb) Level 2,3 = same as Class III
4.2.8.5 (p.336)	Pitch axis control breakout forces	Level 1,2 = ½-1 lb Level 3 = ½ - 2 lb	Class III: Level 1, 2 = ½-2 lb Level 3 = 0-4 lb Class IV: Current requirements
4.2.8.6	Pitch axis control force limits— takeoff (4.2.8.6.1) landing (4.2.8.6.2) dives (4.2.8.6.3) sideslips (4.2.8.6.4)	Not objectionable to the pilot	No data for setting limits; recommend, as a guide, ½ current centerstick limits in all cases

TABLE D-1. PROPOSED REVISIONS TO MIL-STD-1797A REQUIREMENTS FOR SIDESTICKS (continued)

<table>
<tr><th>MIL-STD-1797A, App. A Paragraph (Page No.)</th><th>Subject</th><th>Current Requirements</th><th>Proposed New Requirements</th></tr>
<tr><td>4.5.9.2
(p.476)</td><td>Roll axis control forces to achieve required roll performance</td><td>Not objectionable to the pilot</td><td><table><tr><th>Level</th><th>Class</th><th>Max force (lb)</th></tr><tr><td>1</td><td>IV</td><td>15</td></tr><tr><td></td><td>III</td><td>20</td></tr><tr><td>2</td><td>IV</td><td>20</td></tr><tr><td></td><td>III</td><td>25</td></tr><tr><td>3</td><td>All</td><td>30</td></tr></table></td></tr>
<tr><td>4.5.9.3
(p.478)</td><td>Roll axis control sensitivity</td><td>None</td><td><table><tr><th></th><th></th><th></th><th colspan="2">Sensitivity (deg in 1 sec)/lb</th></tr><tr><th>Level</th><th>Class</th><th>1797A Category</th><th>Min</th><th>Max</th></tr><tr><td>1</td><td>IV</td><td>A</td><td>5</td><td>15</td></tr><tr><td></td><td></td><td>C</td><td>4</td><td>10</td></tr><tr><td></td><td>III</td><td>B</td><td>1.5</td><td>4</td></tr><tr><td>2</td><td>IV</td><td>A</td><td>2</td><td>15</td></tr><tr><td></td><td></td><td>C</td><td>2</td><td>15</td></tr><tr><td></td><td>III</td><td>B</td><td>1.5</td><td>4</td></tr></table></td></tr>
<tr><td>4.5.9.4
(p.496)</td><td>Roll axis control centering and breakout forces</td><td>Class IV: Levels 1 & 2 = ½-1 lb
Level 3 = ½-4 lb
Class III: None</td><td>Same as pitch (see Proposed New Requirements for 4.2.8.5)</td></tr>
<tr><td>4.5.9.5</td><td>Roll axis control force limits—
steady turns (4.5.9.5.1)
dives and pullouts (4.5.9.5.2)
crosswinds (4.5.9.5.3)
steady sideslips (4.5.9.5.4)</td><td>None</td><td>No data for setting limits; recommend, as a guide, ½ current centerstick limits in all cases</td></tr>
</table>

TABLE D-1. PROPOSED REVISIONS TO MIL-STD-1797A REQUIREMENTS FOR SIDESTICKS (concluded)

MIL-STD-1797A, App. A Paragraph (Page No.)	Subject	Current Requirements	Proposed New Requirements
None	Roll axis control forces—control force vs. control deflection	No requirement in MIL-STD-1797A	Class III: Level 1 = 0.67-2 lb/deg (0.5-1.5 deg/lb) Level 2 = 0.2-∞ lb/deg (0-5 deg/lb) Level 3 max = ∞ (0 deg/lb) Class IV: Level 1 = 0.67-2 lb/deg (0.5-1.5 deg/lb) Level 2 = 0.67-∞ lb/deg (0-1.5 deg/lb) Level 3 max = ∞ (0 deg/lb)

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APPENDIX E

DETAILED ANALYSIS OF BANDWIDTH AND DROPBACK REQUIREMENTS FOR FLYING QUALITIES AND PIO PREDICTIONS

A. INTRODUCTION

The pitch attitude Bandwidth criteria were developed for highly-augmented airplanes (Ref. E-1) and are included as alternatives in MIL-STD-1797A. The requirements have continued to evolve since the publication of the military standard, and the current Army helicopter flying qualities specification ADS-33C (Ref. E-2) uses Bandwidth as the basic criterion for pitch, roll, and yaw. In their present form, the Bandwidth criteria — augmented by Gibson's Dropback criterion — are highly effective in defining flying qualities for both pitch attitude and flight path control for all airplane Classes and all Flight Phase Categories.

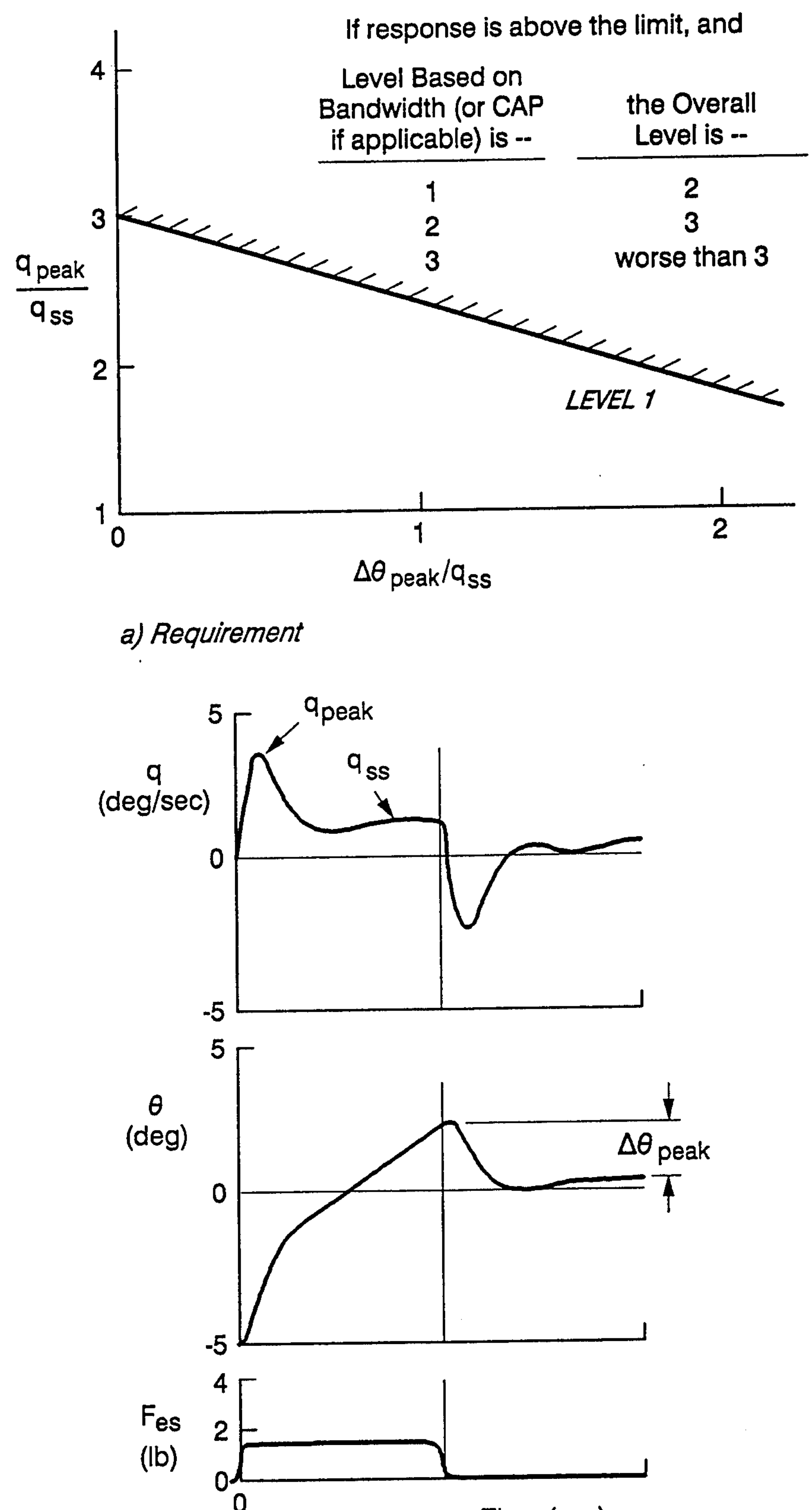
This appendix contains detailed analyses that support several of the Section VI discussions. The contents of this appendix should be viewed as an integral part of Section VI, but they are grouped here only because their inclusion in the main body of the report would make the discussions there unwieldy.

The first part of this appendix documents the development of the pitch attitude Bandwidth, Dropback, and flight path Bandwidth requirements introduced in the main body of this report. Because Bandwidth should be familiar to the reader, the initial focus is on the incorporation of Gibson's Dropback and its effectiveness as an ancillary criterion for both Bandwidth and the "classical" CAP requirements. Following this discussion are descriptions of the supporting data for the specific Bandwidth and Dropback limits.

The last part of this appendix is separated into two subjects: a review of the Smith-Geddes PIO criteria, considered for inclusion in a future revision of MIL-STD-1797A; and an examination of the Bandwidth criteria to support the requirement recommended here. The former is considered relevant given the interest in the Smith-Geddes criteria, and the latter will show the Bandwidth-based requirements to be more successful at predicting tendencies for PIOs.

B. DROPBACK AS A QUASI-OPEN-LOOP CRITERION

The Dropback criterion was developed by Gibson (Ref. E-3) as part of a set of design guidelines for highly-augmented fighter aircraft. Dropback, as it is used here, is defined in Figure E-1; this is a slightly revised definition from that proposed by Gibson in Ref. E-3 and adopted in MIL-STD-1797A.



a) Requirement

b) Definition of Parameters

Figure E-1. Pitch Rate Overshoot and Pitch Attitude Dropback Requirement For Rate and Conventional Response-Types

Dropback is a measure of the mid-frequency response to attitude changes, based on a crossplot of pitch attitude dropback and pitch rate overshoot. Excessive Dropback results in pilot complaints of abruptness and lack of precision in pitch control — complaints common also to aircraft with excessive values of pitch attitude Bandwidth. This commonality of piloting problems led to an analysis of handling qualities data to determine the applicability of the Dropback criterion. When the Bandwidth criteria were developed (Ref. E-1), it was found that several aircraft configurations with very high levels of Bandwidth frequency, ω_{BW}, received Level 2 Handling Qualities Ratings (HQRs). Because the reasons for this were not fully understood at that time, the limits on pitch attitude Bandwidth as published in Appendix A of MIL-STD-1797A show upper limits as dashed lines (Figure E-2).

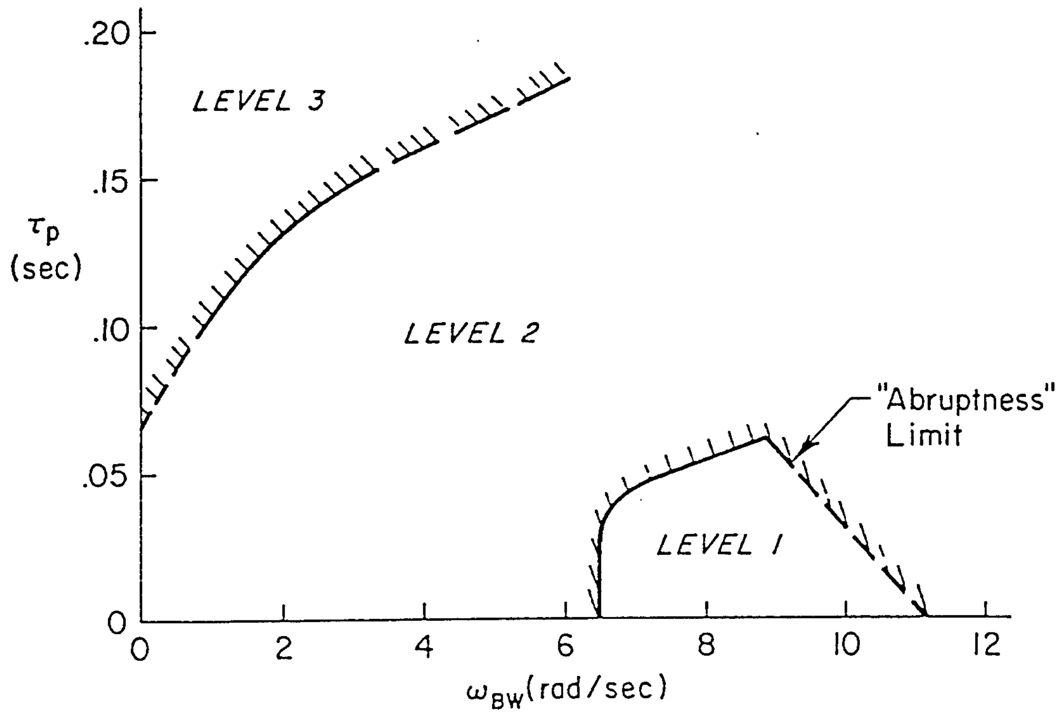
Based on the following evidence, for the next version of MIL-STD-1797 it is recommended that the upper limits on Bandwidth be deleted and Dropback added as an additional element as noted in the main body of this report. It is important to point out that this discussion is applicable <u>only</u> to Conventional and Rate Response-Types: a criterion involving steady-state pitch rate cannot be applied to Attitude Response-Types.

1. Category A, Class IV Fighters (Neal-Smith Data)

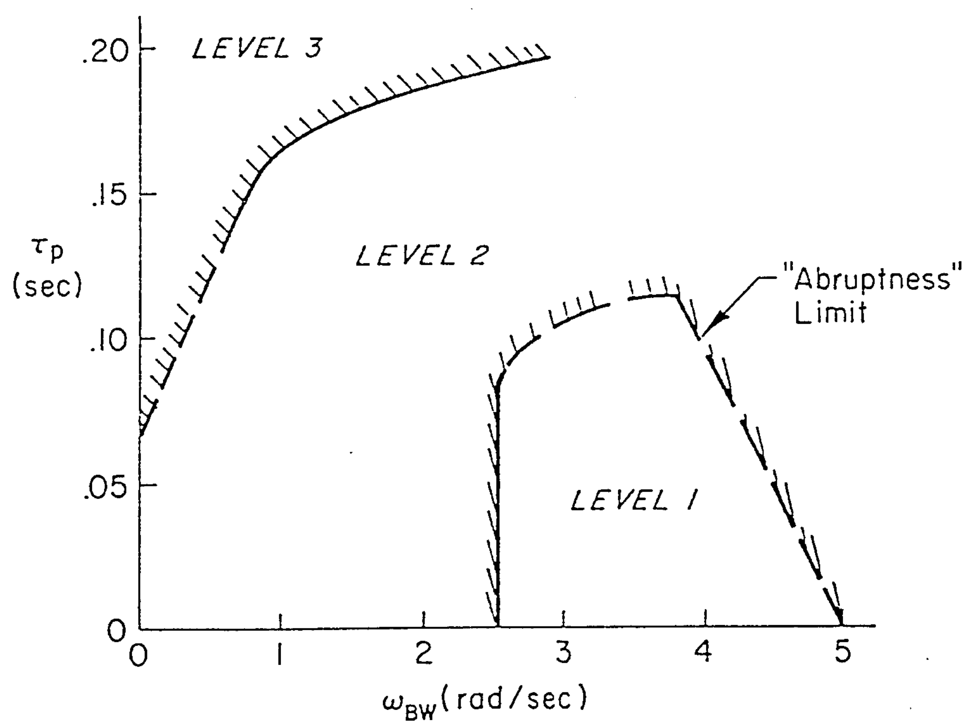
The pitch tracking data of Ref. E-4 were the basis for the Category A pitch attitude bandwidth requirements in the MIL Standard (Figure E-2a). The Dropback characteristics for those configurations evaluated in the Neal-Smith experiment with Level 1 Bandwidth (i.e., greater than 6.5 rad/sec) are plotted in Figure E-3. (The separating limit between acceptable and excessive values of Dropback in Figure E-3 is based on analysis of all the data presented here and not just on the Figure E-3 data alone.) Figure E-3 shows only one of the data points above the Dropback limit with an average HQR better than 3.5 (i.e., Level 1). It is shown later in this appendix that Dropback *alone* is not sufficiently discriminating, since HQRs below the limit may be Level 1, 2, or 3. Thus Dropback is not a stand-alone criterion for *good* handling qualities — some other criteria must also be applied — but it does expose *bad* handling qualities. If the characteristics of a specific airplane are otherwise Level 1 (i.e., pitch attitude and flight path Bandwidths), Dropback must also be low to assure overall Level 1 handling qualities.

2. Category C, Class IV Fighters (LAHOS Data)

The approach and landing data of Ref. E-5 formed the basis for the Category C Bandwidth limits of MIL-STD-1797A (Figure E-2b). The Dropback characteristics for the cases with Level 1 Bandwidths are plotted in Figure E-3. Of these eight cases, two of the three with excessive Dropback received Level 2



a) Category A Flight Phases



b) Category C Flight Phases

Figure E-2. Pitch Attitude Bandwidth Requirements as Published in MIL-STD-1797A

- Plots Show Average HQRs for Configurations With Level 1 Bandwidths
- 15 out of 19 Points Below the Line are Level 1
- 12 out of 14 Points Above the Line are Level 2

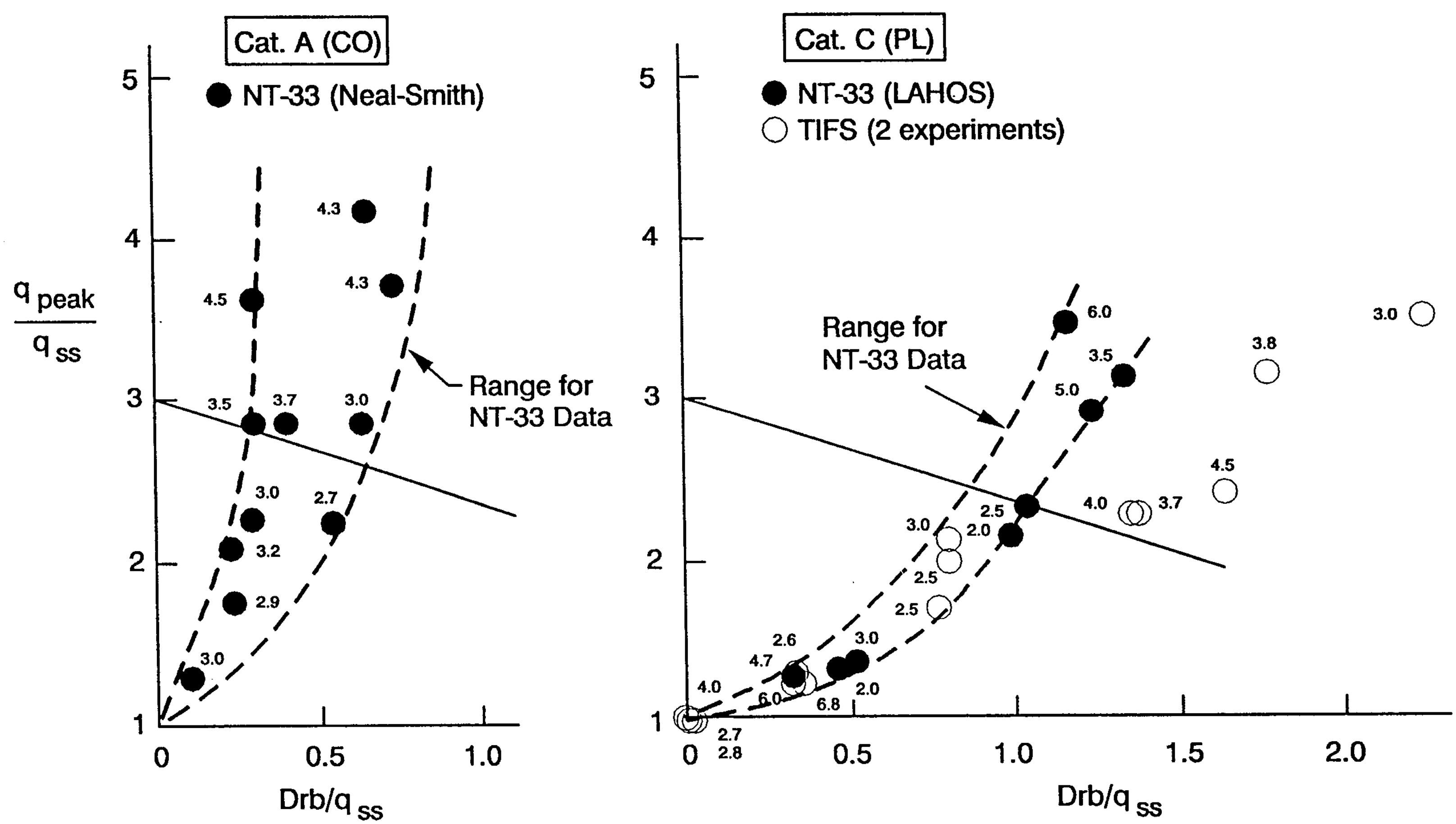


Figure E-3. Dropback Characteristics of High-Bandwidth Configurations

average HQRs and the third was rated 2 and 5, for an average of 3.5; four of the five below the Dropback limit received Level 1 average ratings, and the fifth — which was rated only once — received an HQR of 6. (The HQR 6 case appears to have inadequate flight path Bandwidth, as is shown later.) This supports the removal of an upper limit on Bandwidth (Figure E-2), as long as Dropback is added as a supplementary criterion to prevent excessively abrupt pitch responses.

3. Category C, Class III Transports (TIFS experiments)

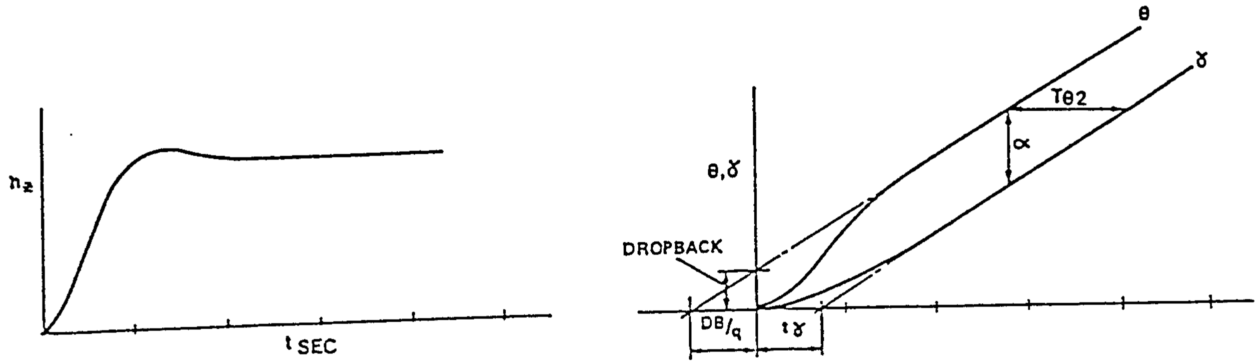
Two flight experiments conducted on the USAF/Calspan Total In-Flight Simulator (TIFS) provide new data for Class III approach and landing operations. These data are not in Appendix A of MIL-STD-1797A, since the experiments were conducted after the writing of the 1982 draft MIL Standard and Handbook (Ref. E-6 in 1984 and Ref. E-7 in 1986). Figure E-3 includes the Dropback characteristics of the otherwise Level 1 configurations.

For the TIFS data in Figure E-3, four of the five cases above the Dropback limit received Level 2 average ratings. The fifth case, with an average HQR of 3.0, was rated by two pilots who assigned HQRs of 4 and 2. Hence even this case was considered to be Level 2 by one of the pilots.

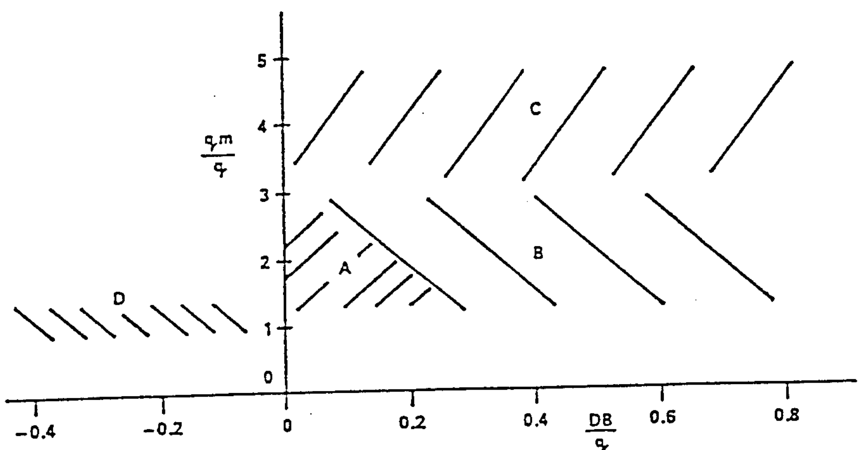
4. Comparison with Gibson's Definition of Dropback

Since the parameters used in the Dropback criterion are time-domain-based, they are subject to many of the fundamental shortcomings of measurement — e.g., what to do if the input is not a pure step, how to account for low-frequency (phugoid) motions, how to define a "steady-state" pitch rate, etc. (see Figure E-1). In fact, the definition of "Dropback" Drb in Figure E-1 differs from the "official" definition in Appendix A of MIL-STD-1797A. Figure E-4 illustrates the Dropback criterion (DB/q) adopted in MIL-STD-1797A, and the boundaries on Dropback recommended for precision tracking. It can be seen from Figure E-4 that the DB/q measure, while less susceptible to low-frequency responses than Drb (Figure E-1), is strongly influenced by time delay: for the attitude response sketched in Figure E-4 (where $DB/q > 0$), addition of time delay will reduce the value of DB/q without affecting pitch rate overshoot at all, while Drb in Figure E-1 is unaffected by time delay. Since "Dropback" is hypothesized as a limit on excessive mid-frequency abruptness, it is desirable to use a parameter that is not strongly affected by time delay — which is separately accounted for by the Phase Delay parameter on Bandwidth.

An additional distinction between Dropback parameters is that Gibson's DB/q can have negative values, Figure E-4, while the Drb of Figure E-1 cannot. Gibson's boundaries in Figure E-4 suggest that



TIME RESPONSE RELATIONSHIPS



A SATISFACTORY
B ABRUPT, BOBBLE TENDENCY
C CONTINUOUS BOBBLING
D SLUGGISH

PRECISION TRACKING : q ~ θ TRENDS

Figure E-4. MIL-STD-1797A Definitions of Dropback

negative dropback is associated with sluggish aircraft — as it must be, since the <u>only</u> way to get DB/q < 0 is with a large time delay, which produces a sluggish response.

5. **Physical Significance of Pitch Rate Overshoot and Pitch Attitude Dropback**

For Conventional and Rate Response-Types, the Dropback parameters are closely related to the familiar "classical" short-period dynamics (e.g., Ref. E-8). For example, examination of Figure E-3 shows a wide range in possible values of Drb/q, especially in going from Category A (left plot) to Category C (right plot), i.e., decreasing airspeed or, equivalently, numerator characteristics as defined by the pitch attitude zero $1/T_{\theta_2}$. As an illustration of this, Figure E-5 is a sketch of the approximate trend in the Dropback parameters as a function of $1/T_{\theta_2}$, based on the Figure E-3 data. This is more clearly seen by using four simple short-period examples, Figure E-6: in the absence of significant high-frequency dynamics or time delays, the Dropback parameters are directly related to the short-period elements. Figure E-6 indicates that for high values of overshoot ratio, increasing Bandwidth results in decreasing Dropback. This is as expected, e.g., Figure E-1: as Bandwidth increases, the same amount of pitch rate overshoot occurs in less time, and hence there is less attitude change. It is also interesting to note from Figure E-6 that constant pitch rate overshoot corresponds to constant values of the product $\omega_{sp}T_{\theta_2}$, which is the frequency separation between the terms in the numerator and denominator of the short-period approximation. Hence overshoot ratio is effectively a limit on this frequency separation. On the other hand, Dropback Drb/q is inversely proportional to short-period frequency, and therefore an upper limit on Dropback corresponds to a lower limit on ω_{sp}. Figure E-6 also shows the variation in Dropback with $1/T_{\theta_2}$ noted in Figure E-5.

6. *Using Dropback to Resolve Discrepancies Between "Classical" Data and Data for Highly Augmented Aircraft*

Most of the discussion for the short-term pitch requirements in Appendix A of MIL-STD-1797A centers around the two flight experiments mentioned above: the Neal-Smith (Ref. E-4) and LAHOS (Ref. E-5) studies. The results of these studies require considerable interpretation, and they are the primary motivation for many of the alternative pitch criteria in the Standard and elsewhere. At the time the proposed Standard and Handbook (Ref. E-9) were written, these data presented a significant challenge to the handling qualities engineer: the criteria derived using these results as guides (including Bandwidth and the Neal-Smith criteria, among many others) worked well for the data in the two references — but were not as successful for the more "classical" data upon which the traditional flying qualities

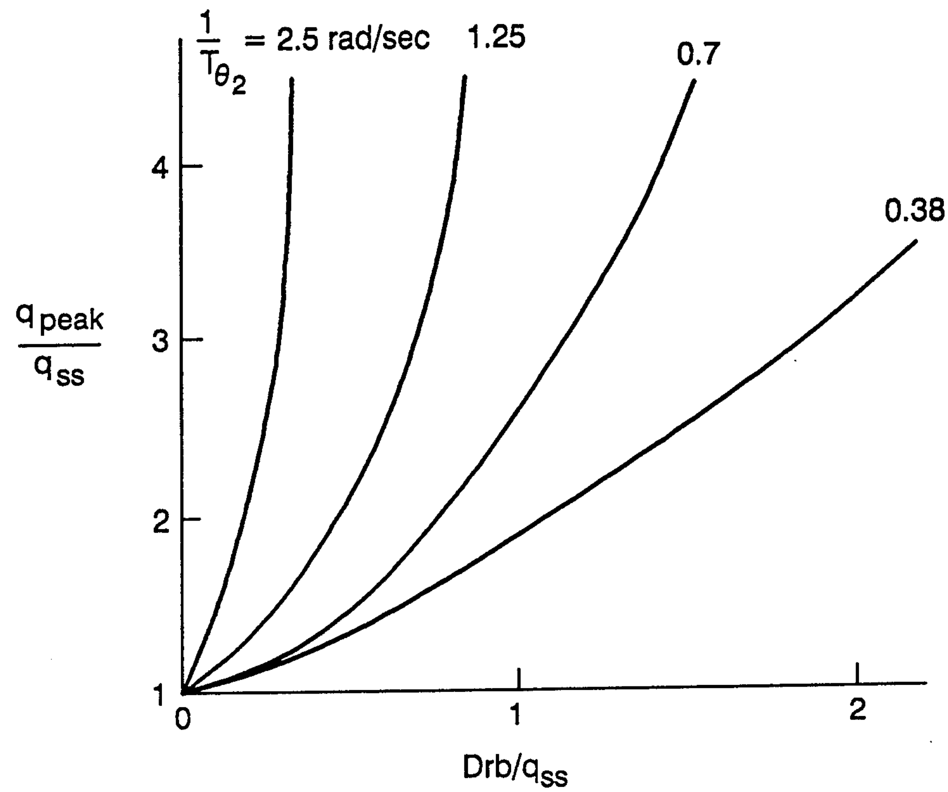


Figure E-5. Approximate Trend in Dropback Parameters with Numerator Zero $1/T_{\theta_2}$

requirements of MIL-F-8785C were based. Conversely, the MIL-F-8785C criteria did not apply very well to these two data sets.

With the addition of Dropback as a supplement to the pitch requirements of MIL-STD-1797A, these discrepancies are removed entirely. For example, a common criticism of the Bandwidth requirements for Category A (i.e., Figure E-2a) is that they are much too stringent for most airplanes to meet. The data upon which these requirements are based come from the Neal-Smith experiment. The limits as drawn were based heavily on the grouping of Level 2 ratings for Bandwidths around 6 rad/sec – but as is shown below, the majority of these cases have excessive levels of pitch attitude Dropback, so Level 2 ratings are expected. With Dropback adopted as a supplementary requirement to Bandwidth, many of the questions about the Figure E-2a limits are clarified. The new Category A Bandwidth boundaries developed in this report have a Level 1 minimum value of 3.5 rad/sec – consistent with the "classical" airplane data (see, e.g, Appendix A of MIL-STD-1797A). Similarly, new limits have been drawn for Category C (precision landing) that are more in line with the "classical" data.

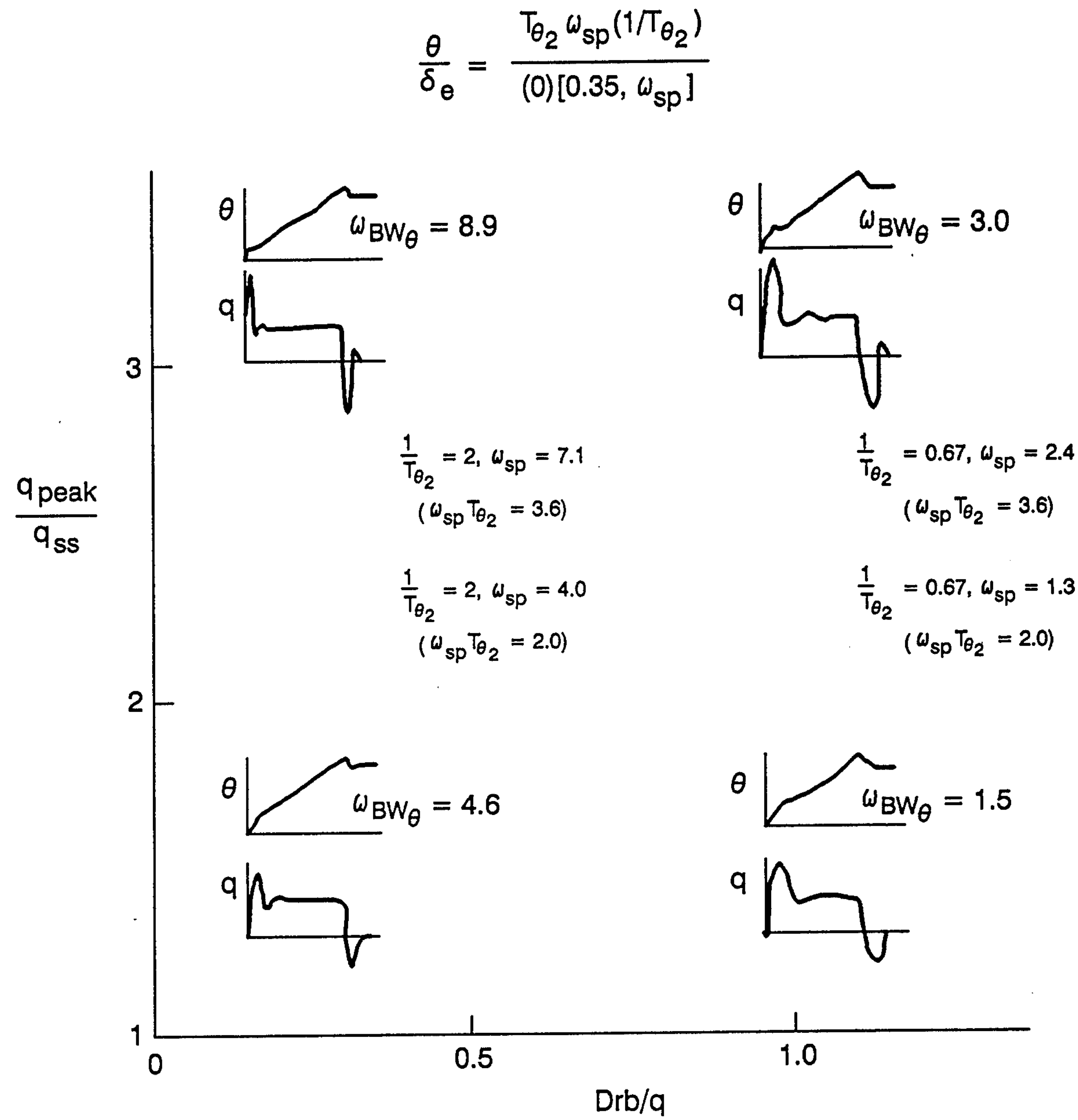


Figure E-6. Dropback Characteristics of Conventional Aircraft for $\zeta_{sp} = 0.35$ (No Time Delay)

Addition of Dropback as a supplementary requirement also resolves apparent discrepancies over the use of equivalent-system techniques in conjunction with the MIL-F-8785C criteria (CAP plus equivalent damping ratio and time delay). For example, Ref. E-10 indicates that equivalent-systems applications to the Neal-Smith data result in a requirement to increase the Level 1 minimum on short-period damping ratio, ζ_{sp}, from 0.35 to 0.5 for Category A operations, even though the 0.35 value is well-supported by "conventional" aircraft data. Hence, these data raised the dilemma of what constitutes a "highly-augmented" aircraft.

Most of the configurations in question have certain unusual characteristics ("humps" in the frequency response near the short-period mode) and have been analyzed in great detail (see, e.g., Ref. E-10). Analysis of these cases shows that many of them also have high Dropback — and can, therefore, be separately dealt with by using Dropback as a supplementary requirement. As an illustration, Figure E-7 (taken with minor revisions from MIL-STD-1797A) shows the equivalent-systems-derived damping ratio and CAP for the Neal-Smith configurations with high-Dropback cases indicated by solid symbols. This figure clearly illustrates that configurations with high Dropback also exhibit either low equivalent short-period damping, high equivalent short-period frequency (high values of CAP), or both. If Dropback is used as a supplementary requirement, the dilemma over the apparent need for a higher damping ratio is eliminated.

C. DEVELOPMENT OF BANDWIDTH AND DROPBACK REQUIREMENTS FOR TRANSPORTS (CLASS III) FOR PRECISION LANDING (CATEGORY C)

1. Review of the Data Base

a. TIFS Data

The Bandwidth, Phase Delay, and Dropback boundaries are based primarily on two NASA-sponsored studies using in-flight simulation to investigate the flying qualities of transport aircraft in the approach and landing task (Refs. E-6 and E-7). The aircraft used in both experiments was the Air Force/Calspan Total In-Flight Simulator (TIFS). The 1984 experiment explored the effect of different flight control system gains and feedback architecture applied to seven different aerodynamic models. The approach in the 1986 experiment was to define the exact model pole/zero placement directly to achieve a desired command response. The details of both experiments follow.

1984 Experiment. — The aircraft simulated in this experiment was defined to be a generic 193,000 lb transport with relaxed static stability. Seven different bare aircraft models were implemented,

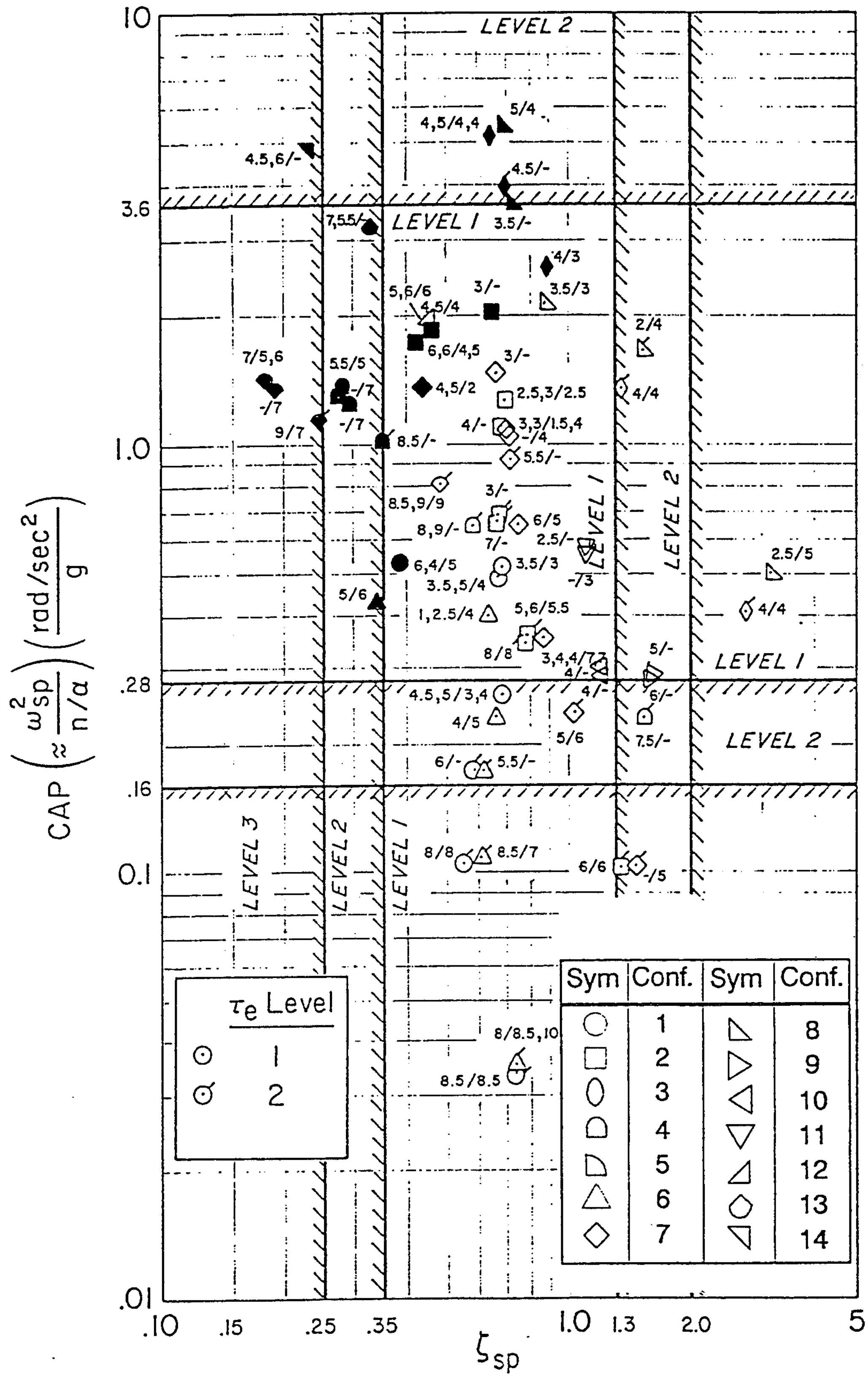


Figure E-7. Equivalent-System Damping and Frequency for Neal-Smith Configurations
(Solid Symbols Denote Excessive Dropback)

studying the effects of variations in $1/T_{\theta_2}$ (0.4, 0.7, and 1.0 rad/sec) and ω_{sp} (1.8 and 2.8 rad/sec), neutral static stability, and location of the center of rotation. Several flight control configurations were applied to the aircraft models in various combinations.

Additional comments:

- The aircraft thrust response was set up to be symmetric, having a first order response of time constant 1.0 sec, and was considered "...transparent to the overall pitch task."
- The lateral-directional system was fixed throughout the experiment as an augmented system with Level 1 flying qualities.
- The aircraft controls consisted of a standard wheel yoke and rudder pedals. The feel system was a second order system with

$$\frac{\text{control position}}{\text{control force}} = \frac{25^2}{[0.7,\ 25]}$$

The task in the 1984 experiment was a precision approach, flare, and landing. After being given control of the aircraft on the downwind leg, the evaluation pilot made a visual turning approach to intercept the ILS glideslope 1.5 to 2 miles from touchdown. The final approach began with a 200 ft lateral offset. The pilot was required to track the ILS Glideslope beam to a point 3500 ft from touchdown to disallow "duck under." During the approach, a computer-generated (1-cos ωt) angle-of-attack gust was applied. The pilot was required to align with the runway centerline and land the aircraft, after which the safety pilot initiated a climbout.

The approach and landing task is depicted in Figure E-8. The touchdown area was partitioned into "desired" and "adequate" areas as shown. In addition, the pilots were instructed to hold airspeed as close as possible to 132 KIAS during the approach. Holding the airspeed to within ±3 KIAS at the altitude "barrier" passage was considered "desired" and a variation of ±5 KIAS was considered "adequate." Furthermore, the sink rate at touchdown was rated as "desired" if 0-3 fps; and "adequate" if 3-6 fps.

1986 Experiment. — The simulated generic transport model was the same as that used in the 1984 experiment. Rather than wrapping control loops around a predefined airframe model, however, the poles, zeroes, and sensitivity of the closed loop system were directly set *a priori*. Specifically, the values of ζ_{sp}, ω_p, ω_α, $1/T_{\theta_2}$, and N_z/α were perturbed in various combinations about a known Level 1 base system. The force-feel and lateral-directional systems, as well as the flight controls, were essentially those of the

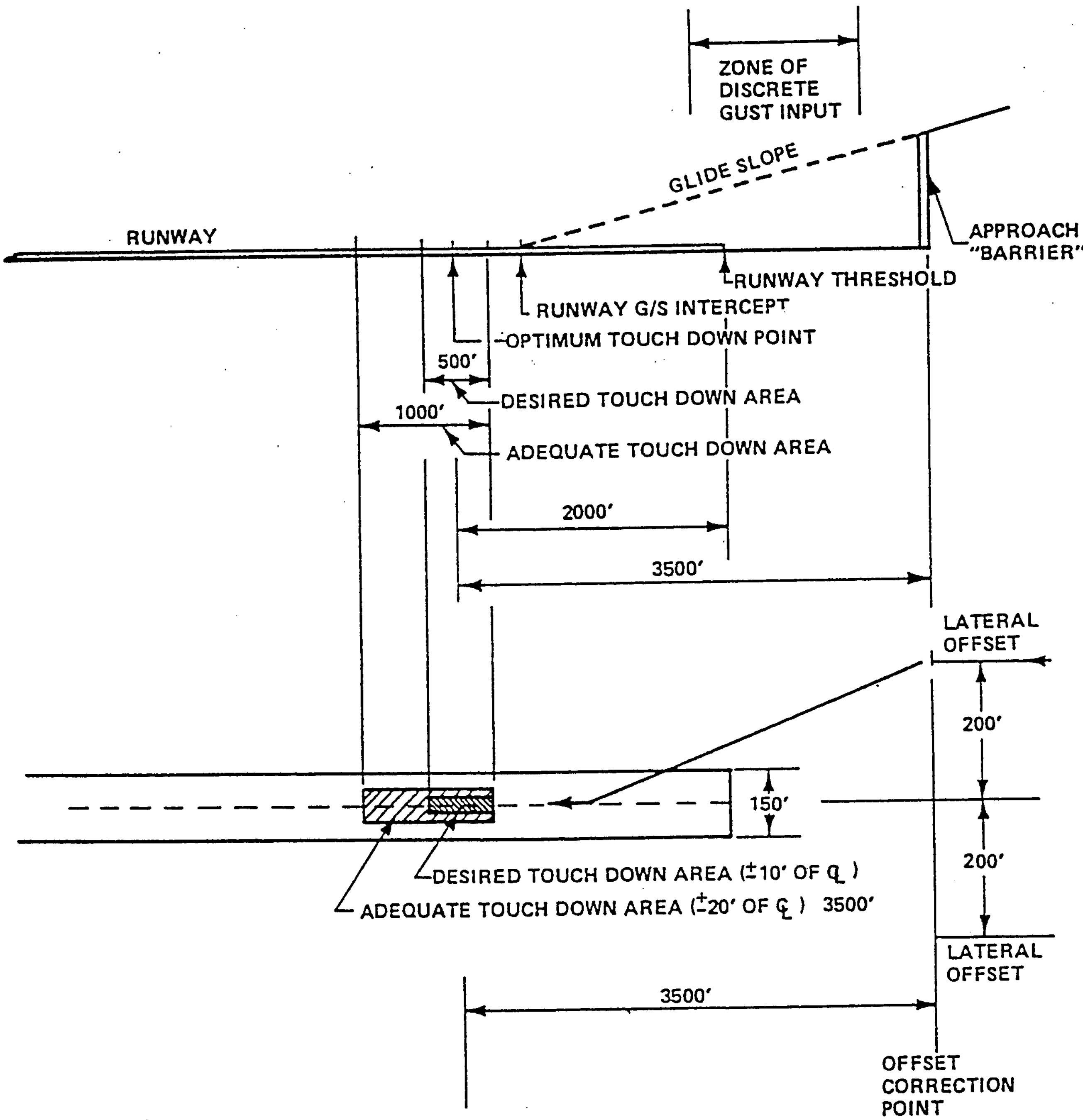


Figure E-8. TIFS Approach and Landing Task

1984 experiment. Thrust was designed to respond in the speed degree of freedom only (for an idealized frontside configuration), and had a first-order time constant of 0.2 sec. The task in the 1986 experiment was exactly the same as that for the 1984 experiment (Figure E-8). This set of TIFS data has the advantage that more pilots —as many as six, compared to two in the 1984 study— participated in the experiment, which justifies a higher confidence level for certain ratings.

b. Large Aircraft Data

C-5A Data. — Two in-flight simulation studies were performed during the design phase of the Boeing C-5A heavy military transport, around 1965. The first was conducted by the Cornell Aeronautical Laboratory (using a variable-stability B-26) to gain an understanding of the control problems faced by pilots of the new aircraft during the landing task (Ref. E-11). This was later expanded upon by Boeing in a parallel series of ground-based simulations and flight tests using a Boeing 367-80 (prototype of the 707) modified for in-flight simulation of the C-5A (Ref. E-12).

The Boeing simulations considered a matrix of variations in longitudinal short period frequency and damping ratio. The data included here from the Cornell investigation cover short period frequency variations only.

The pilots participating in the Cornell test program were presented the following task, quoted from Ref. E-11:

> "The evaluation task for this program was an ILS approach to low altitude at the airfield. The evaluation pilot flew under the hood for some time prior to intercepting the outer marker. He went under the hood while on a dogleg outside the outer marker and approximately 1000 feet above outer-marker intercept altitude. Thus, the pilot began the ILS approach by having to reduce his altitude and to acquire the localizer prior to glide slope interception at ILS approach down to 200 feet above runway altitude. At the 200-foot point, he removed the hood and proceeded VFR to the airfield and a very low approach. The approach was carried sufficiently low that the pilot had to initiate a flare, and, in some instances, the flare was continued to touchdown or almost to touchdown."

The following is taken from Ref. E-12 and describes the task the evaluation pilots were required to perform during the Boeing experiment:

1. Establish a 500 fpm rate of descent and perform a flare (repeated for 1000 fpm).

   This maneuver evaluated the flight path and speed control characteristics and the flare capabilities of each configuration.

2. Perform a 'roller coaster' maneuver.

   This maneuver evaluated the pitch rate response, pitch damping, and capabilities of each configuration.

3. ILS Approach

   This maneuver evaluated the precision control characteristics. A longitudinal offset was performed by flaring to level flight at 1000 ft altitude and then pushing over and recapturing the glide slope. This maneuver evaluated the large amplitude correction maneuver capabilities."

Clearly, both sets of tasks in the C-5A experiments were much less stringent than those performed by the evaluation pilots in the TIFS experiments. There were no supplementary lateral-correction, gust-alleviation, or airspeed-hold tasks, all of which were present in the TIFS experiments. There were no "desired" and "adequate" touchdown point areas specified; the pilots were not necessarily even required to land. While the C-5A results have proven useful in establishing the correlations between Bandwidth and flying qualities, the nature of the experiments warrants caution in interpreting the results when comparing across databases.

The test pilots in both the Cornell and Boeing programs rated the configurations using the CAL ten-point rating scale, which is similar to, but not the same as, the Cooper-Harper HQR scale (Ref. E-13). It has been common in the past to simply plot CAL and Cooper-Harper ratings on the same plot, but this is not correct. A procedure was developed for this effort to convert from the CAL and Cooper rating scales to equivalent HQRs. This procedure is described below. This difficulty, combined with the aforementioned lack of specificity of the task, lowers the credibility of the C-5A data as compared to the TIFS data.

Bandwidth and Phase Delay for these data were calculated directly from knowing the θ/F_s and γ/F_s transfer functions simulated. Because all configurations exhibited a lightly damped phugoid, Dropback was calculated using a constant airspeed approximation. All cases were classified as conventional response-types.

Hypersonic Transport Data. — The Ref. E-14 simulation evaluated candidate response-types for a Task-Tailored Flight Control System for the landing of a large, advanced, hypersonic transport. A general set of vehicle dynamics typical of this class of aircraft was utilized, and variations of three basic advanced response-type categories were studied. In addition to Rate Command/Attitude Hold and Attitude Command/Attitude Hold, the relatively untested Flightpath Command/Flightpath Hold and Flightpath Rate Command/Flightpath Hold categories were explored in various ways.

All of the evaluations took place using the moving-base (hexapod) Visual/Motion Simulator at NASA Langley Research Center. Initial tests were conducted using a transport-style column and wheel as the primary flight control device, but most of the evaluations used a centerstick. The longitudinal force-feel system for the column was a second-order actuator:

$$\frac{\text{control position}}{\text{control force}} = \frac{50.41}{[1.15, 7.1]}$$

and that for the centerstick was:

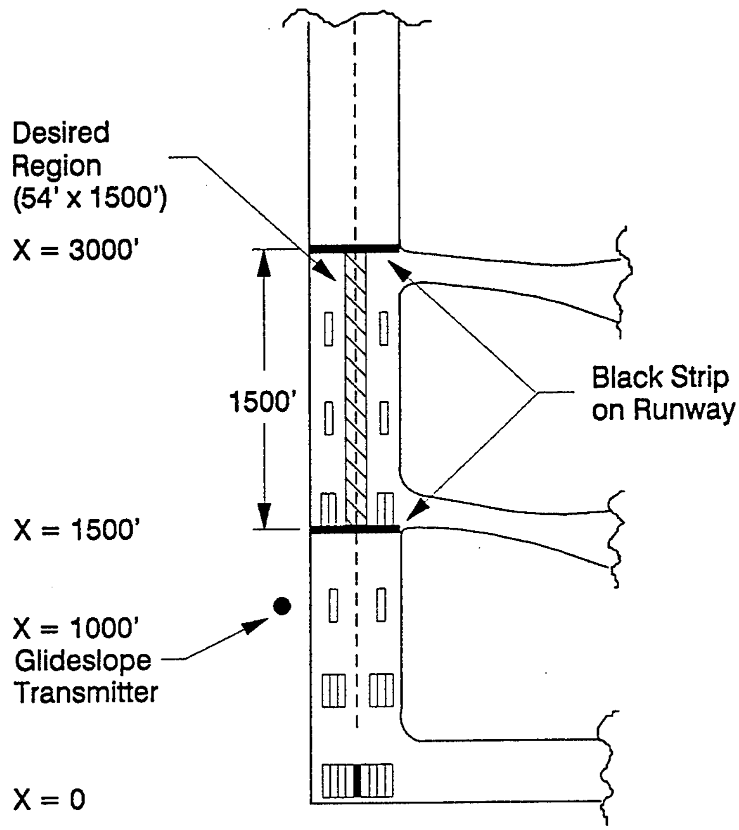
$$\frac{\text{control position}}{\text{control force}} = \frac{3.75}{(3.75)}$$

The pilot was provided with high-fidelity sound cues (i.e., engine noise), as well as motion and visual information. The task was a precision manual flare and landing with touchdown position and sink rate requirements as depicted in Figure E-9. Additionally, the pilots were required to maintain airspeed at 178 ±10 knots during the approach, and were not allowed to "duck under," or fly an approach flatter than the three-degree ILS glideslope. A light-to-moderate level of turbulence was applied, and runs were made in conditions of no wind, high head- and tailwind, and heavy windshears.

<u>SST Data.</u> – The set of data in Ref. E-15 is a result of a NASA investigation of flying characteristics of fixed and variable-geometry SST designs, simulated in-flight on a Boeing 367-80. Added to the basic aircraft configuration were various combinations of variable geometry, pitch rate augmentation, aft center of gravity location, and supplementary angle of attack feedback.

The following excerpt from Ref. E-15 summarizes the approach and landing task performed by the evaluation pilots:

> "For this task, an intercept of the localizer was made with landing gear down approximately 8 miles from the runway at an altitude of 1500 feet. The flaps and airspeed were then adjusted for the landing approach as required by the simulation. At the intercept of the glide slope, approximately 5 miles from the runway, a descent was initiated and the pilot attempted to fly the prescribed flight path as closely as possible down to approximately 200 feet and, if conditions were favorable, continue visually to touchdown. Some tests were made with the localizer offset 200 feet from the runway center line during the approach to evaluate the lateral maneuverability. Following the simulated IFR breakout at 200 feet with the lateral offsets, the pilot performed a visual sidestep maneuver in order to line up with the runway. Other tests were also made with square-wave vertical offsets of the glide slope approximately halfway down the glide slope to study the speed-thrust stability and longitudinal maneuverability while the pilot was under the hood."



Desired Performance:

$$\left.\begin{aligned} X_{TD} &= 1500' - 3000' \\ Y_{TD} &= \pm 27' \\ \dot{h}_{TD} &\leq 6 \text{ ft/sec} \end{aligned}\right\} \text{7 out of 10 runs}$$

Adequate Performance:

$$\begin{aligned} X_{TD} &= 0 - 5000' \\ Y_{TD} &= \pm 87' \\ \dot{h}_{TD} &\leq 8 \text{ ft/sec} \end{aligned}$$

Figure E-9. Hypersonic Transport Touchdown Performance Requirements

The test sequence also included a series of basic VFR maneuvers at altitude, which unfortunately were factored into the test pilots' evaluations, casting some doubt on their applicability to Category C MTEs exclusively. Again, there were no specific performance requirements for landing, and landings were performed only "if conditions were favorable." This experiment had notable elements in common with the TIFS experiments; for example, the lateral offset correction as a secondary task, and the flare was continued all the way to touchdown. The data are considered inferior to the TIFS data for the purposes of this analysis, however, for at least two reasons: the Cooper scale was used by the evaluation pilots to rate the configurations, which necessitates a translation to HQRs; and the approach and landing task was not as stringent and not rated separately from the other VFR maneuvers.

c. Supplementary Aircraft Data

A third set of data is presented here, although it was *not* utilized in the placement of the Bandwidth and Dropback boundaries. This consists of information on currently operating transport-size aircraft (with two exceptions: the XB-70A and the C-17). The shortcomings of this collection of vehicle data are that, in most cases, precise identification of the dynamics was difficult or uncertain and appropriate pilot ratings were unavailable.

2. Conversion of Cooper and CAL Pilot Ratings to Cooper-Harper Handling Qualities Ratings

Prior to the introduction of the Cooper-Harper Handling Qualities Rating scale in the 1960s (formally published in Ref. E-16), piloted handling-qualities evaluations made use of a variety of different numerical rating scales (see Ref. E-13 and Figure E-10). The use of the HQR scale in flight and simulation testing has become standard, and a general set of guidelines for applying the scale has evolved, e.g., definitions of desired and adequate performance, clear delineation of the task, etc. Many of these specific guidelines were not applied in handling-qualities experiments before the 1970s.

There is, nevertheless, a very large body of data generated prior to the adoption of the HQR scale. Concurrent use of pre- and post-HQR data has been tenuous at best because of the two limitations outlined above, i.e., the use of differing rating scales, and the use of different task definitions and performance standards. It has been standard to simply assume a commonality between all of the major scales, e.g., a 6 is a 6, whether it is from the HQR scale or not. (Exceptions to this are sometimes found in the literature; for example, in the 1969 Background Information and User Guide [BIUG] for MIL-F-8785B [Ref. E-17], it was recognized that a rating of 5.5 on the Cooper pilot rating scale was equivalent to a 6.5 on the then-new HQR scale.]

Operating Conditions	Adjective Rating	Numerical Rating	Description	Primary Mission Accomplished	Can be Landed
Normal Operation	Satisfactory	1	Excellent, includes optimum$^{1.0}$	YES	YES
		2	Good,$^{3.7}$ pleasant to fly$^{3.7}$	YES	YES
		3	Mildly unpleasant characteristics$^{5.7}$	YES	YES
Emergency Operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics$^{6.0}$	YES	YES
		5	Unacceptable for normal operation$^{7.1}$	Doubtful	YES
		6	Acceptable for emergency condition only*$^{7.5}$	Doubtful	YES
No Operation	Unacceptable	7	Unacceptable even for emergency condition*$^{8.0}$	NO	Doubtful
		8	Unacceptable — dangerous$^{9.0}$	NO	NO
		9	Unacceptable — uncontrollable^{10}	NO	NO
		10	Motions possibly violent enough to prevent pilot escape	NO	NO

*Failure of a stability augmenter

a) Cooper Pilot Rating Scale

Figure E-10. Examples of Pilot Rating Scales (Numbers Beside Adjective Description Correspond to ψ Scale Equivalents)

Category	Adjective Description Within Category		Numerical Rating
	Satisfactory	Excellent$^{1.0}$	1
		Good$^{3.7}$	2
		Fair$^{5.3}$	3
Acceptable		(ask that it be fixed)$^{6.0}$	
	Unsatisfactory	Fair$^{5.3}$	4
		Poor$^{7.4}$	5
		Bad$^{8.0}$	6
		(won't buy it)$^{8.0}$	
	Flyable	Bad[a] $^{8.0}$	7
		Very bad[b] $^{8.3}$	8
		Dangerous[c]	9
Unacceptable		(won't fly it)$^{9.0}$	
	Unflyable	Unflyable^{10}	10

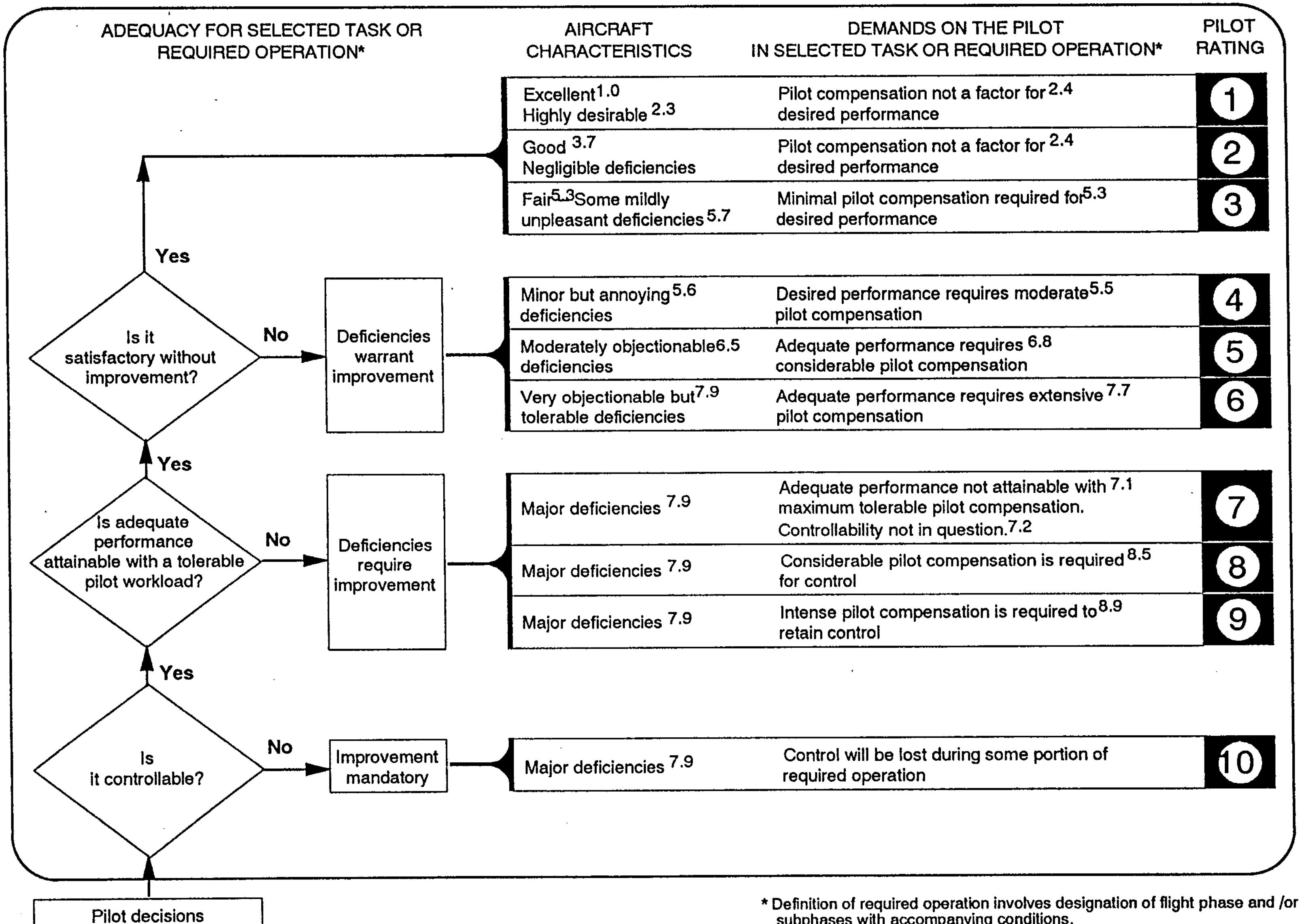
[a]Required Major Portion of Pilot's Attention

[b]Controllable only with a Minimum of Cockpit Duties$^{8.5}$

[c]Aircraft just Controllable with Complete Attention$^{8.9}$

b) Cornell Aeronautical Labs (CAL) Pilot Rating Scale

Figure E-10. Examples of Pilot Rating Scales (Numbers Beside Adjective Description Correspond to ψ Scale Equivalents) (Continued)



c) Cooper-Harper HQR Scale

Figure E-10. Examples of Pilot Rating Scales (Numbers Beside Adjective Description Correspond to ψ Scale Equivalents) (concluded)

There have been three alternative approaches to applying the data generated before the introduction of the HQR scale: 1) use the non-HQR-based pilot ratings as if they were exactly equivalent to HQRs; 2) use the ratings with some pre-judged bias or correction factor (as in the MIL-F-8785B BIUG); or 3) don't use the data at all.

There is no method available to properly account for the impact of task definition on pilot opinion. It is possible, however, to make some corrections for pilot ratings, by converting the ratings from the different scales to an equivalent HQR.

The following is a recommended procedure for converting the numerical ratings from two of the most common pre-HQR scales, the Cooper and CAL scales, to equivalent ratings on the HQR scale. To do this extensive use is made of the work of McDonnell (Ref. E-18). McDonnell developed a method for converting the ratings on the ordinal, metathetic (see Ref. E-13) HQR scale to an interval scale, the ψ scale. This process made use of 64 common handling-qualities adjectival descriptions, some of which appear explicitly on the scales in Figure E-10. A similar process has been performed for converting the Cooper and CAL scale numerical ratings to the ψ scale — from which it is trivial to further compute the equivalent HQR.

The procedure requires the identification of common adjective descriptions occurring on both the subject pilot rating scale and in McDonnell's list. For these descriptions a one-to-one conversion from pilot rating to ψ scale value can be made. As will be seen, the greatest challenge in this process has been in this transference from each of the pilot rating scales to the ψ scale. This process has, at times, required liberal use of engineering judgment, because many of the descriptors on the Cooper and CAL scales simply do not appear in McDonnell's list. In such a case it has been necessary to determine either similar *words* or similar *intent*, or, failing this, to simply leave the descriptor uninterpreted, i.e., ignore it entirely.

There are many variants of the two primary rating scales, the Cooper and CAL scales. The CAL (or Harper) scale, especially, evolved from that shown in Figure E-10b (which is, itself, a slight variation on earlier versions) to a form quite similar to the final HQR scale. The scales illustrated in Figure E-10 were used for this analysis, since they are representative of the scales used in the experiments described above.

a. <u>Conversion of Cooper Ratings to Equivalent HQRS</u>

The Cooper pilot rating scale is, in some ways, the easier of the two pre-HQR scales to convert to equivalent HQRs. The adjective descriptions are more complete (contrast the phrases in Figure E-10a with the one-word descriptors in Figure E-10b) and some have almost exact matches in McDonnell's

descriptions list. In other ways, however, this scale is more challenging. For example, there are obvious conflicts in the different columns of the scale (e.g., ratings of 5 and 6 suggest that it is doubtful the primary mission can be accomplished, yet the aircraft can still be landed; for this discussion, the primary mission *is* the landing). In addition, for ratings worse than 7 the concern is not over the difficulty in performing the landing, but in staying alive — a much more extreme approach than that taken with either the CAL or Cooper-Harper scale. These conflicts and mission judgments make this a difficult scale to convert, since some determination of *intent*, as well as wording, must be applied. (In his analysis of pilot rating scales, McDonnell lumped the Cooper and Cooper-Harper scales together because of their common phraseology; it is clear, however, that this commonality breaks down for ratings worse than about 4.)

Table E-1 lists the descriptors from the Cooper scale and the equivalents selected from McDonnell's ψ list. The comparative descriptors for Cooper ratings of 1, 2, and 3 are very close. For all other ratings, however, there are no clear comparable descriptors in the ψ scale list. For Cooper ratings of 4 through 8 a generous amount of engineering judgment was required. For a Cooper rating of 9, while the term "uncontrollable" was included in the ψ scale study, it actually has no assigned ψ value since ψ is an open-ended scale. For our analysis we have assigned this descriptor a ψ value of 10. Finally, the Cooper-rating 10 descriptor, "Motions possibly violent enough to prevent pilot escape," is clearly much worse than a 10 on the ψ scale — how much worse cannot be determined, since the most extreme descriptor in the ψ study was "uncontrollable."

The tabulated Cooper and ψ ratings in Table E-1 provide us with the means for converting from the Cooper scale to the ψ scale. For the final step — transference from ψ to HQR — we can use the correlations documented in Ref. E-18 and refined in Ref. E-13. From Ref. E-13, a very good formula relating ψ to HQR was found to be

$$\text{HQR} = 0.11\psi^2 + 0.68$$

A nomograph for performing this conversion process is shown in Figure E-11. The right side of this nomograph is a crossplot of the Cooper ratings and ψ scale values from Table E-1. On the left side is the regression line for the conversion to HQRs given above. From this nomograph, as the example shows, it is possible to convert from any Cooper rating to its HQR equivalent, and vice versa, by first going through the ψ scale.

TABLE E-1. CONVERSION OF COOPER SCALE TO ψ SCALE

COOPER RATING	COOPER DESCRIPTOR	ψ VALUE	ψ DESCRIPTOR
1	Excellent, Includes Optimum	1.00	Excellent Handling Qualities
2	Good, Pleasant to Fly	3.70 3.71	Good Handling Qualities Pleasant Handling Qualities
3	Satisfactory, but with some Mildly Unpleasant Characteristics	5.66	Some Mildly Unpleasant Characteristics
4	Acceptable, but with Unpleasant Characteristics	6.04	Improvement is Requested
5	Unacceptable for Normal Operation [Primary Mission Accomplished? "Doubtful"]	7.08	Pilot Compensation Required for Acceptable Performance in Mission is too High
6	Acceptable for Emergency Conditions Only [Primary Mission Accomplished? "Doubtful"]	7.48	Requires Substantial Pilot Skill and Attention to Retain Control and Continue Mission
7	Unacceptable Even for Emergency Condition [Can be Landed? "Doubtful"]	8.00	Mandatory Improvement Required
8	Unacceptable — Dangerous [Can be Landed? "No"]	9.00	Nearly Uncontrollable
9	Unacceptable — Uncontrollable [Can be Landed? "No"]	10.0	Uncontrollable
10	Motions Possibly Violent Enough to Prevent Pilot Escape	—	(No ψ Equivalent)

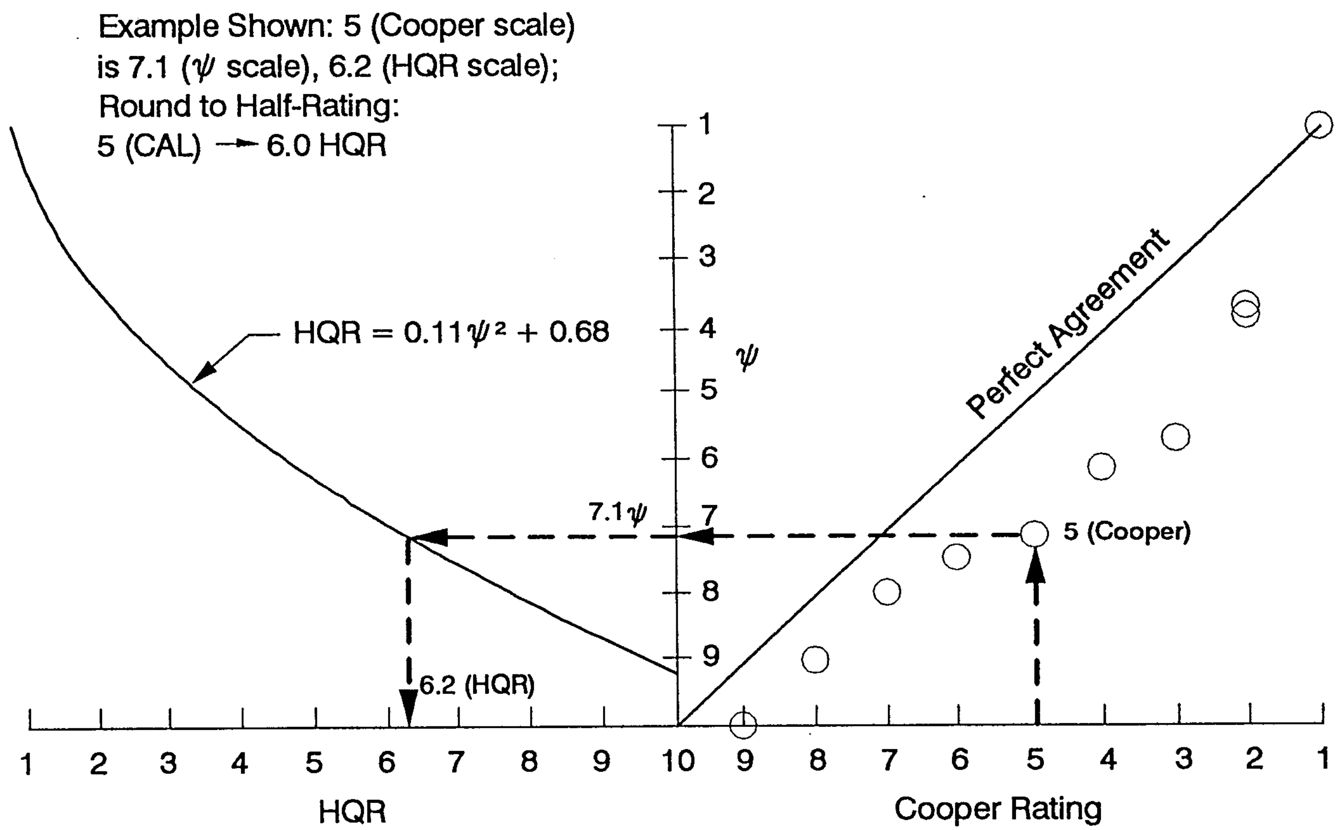


Figure E-11. Conversion of Cooper Ratings to HQRs Through the ψ Scale

For those references that contained Cooper ratings, the conversion to equivalent HQRs was performed as illustrated on Figure E-11. The HQR equivalents were always rounded to the nearest half-rating to more correctly represent the format of HQRs. (This was done even if the resulting equivalent HQR was 3.5 or 6.5 – ratings that should not be given when the HQR scale is actually used for assessment.)

b. Conversion of CAL Ratings to Equivalent HQRS

The procedure for converting CAL pilot ratings to equivalent HQRs was essentially identical to that for Cooper ratings described above. As with the Cooper scale, there were instances where exact matches in the adjectival descriptors between the CAL and ψ scales could not be identified. Table E-2 summarizes the descriptors used.

Some earlier versions of the CAL scale do not include the terms shown in parentheses in Table E-2. These phrases are also not included in the list of ψ descriptors. The interpretations for these are, therefore, open for debate. In addition, there is no ψ-scale equivalent for the CAL-rating 9 descriptor of "Dangerous [Aircraft Just Controllable With Complete Attention];" and, as for the Cooper scale, a CAL rating of 10 has been assumed to be equivalent to a ψ scale value of 10.

The nomograph for converting between CAL ratings and HQRs is given in Figure E-12. This figure shows the CAL-to-ψ values from Table E-2 and the ψ-to-HQR formula listed above.

c. Definition of Flying Qualities Levels

While all ratings in this appendix are either true HQRs or equivalent, converted HQRs, it is possible through the nomographs of Figures E-11 and E-12 to identify the effective pilot ratings corresponding to the military standard definitions of Levels 1, 2 and 3. For the Cooper-Harper HQR scale, these Levels correspond to average ratings of 3.5, 6.5, and 9. There is some slight disagreement about the Level 3 rating: an average HQR of 9.5 corresponds to the region between the major divisions of the decision tree (Figure E-10c), consistent with 3.5 and 6.5. On the other hand, strict interpretation of an average of 9.5 is that the airplane is a solid 10 half the time – and a 10 implies loss of control, inconsistent with the definition of Level 3. Likewise, some prefer to divide the Levels at 8.5, or even 8, since a 9 implies difficulty in retaining control and even this hints at more severe conditions than those suggested by the definition of Level 3. For the following, we have used 9 as the Level 3 divider for convenience.

TABLE E-2. CONVERSION OF CAL SCALE TO ψ SCALE

CAL RATING	CAL DESCRIPTOR	ψ VALUE	ψ DESCRIPTOR
1	Excellent	1.00	Excellent Handling Qualities
2	Good	3.70	Good Handling Qualities
3	Fair	5.34	Fair Handling Qualities
(3-4)	(Ask That it Be Fixed)	6.04	Improvement is Requested
4	Fair	5.34	Fair Handling Qualities
5	Poor	7.39	Poor Handling Qualities
6	Bad	7.97	Bad Handling Qualities
(6-7)	(Won't Buy It)	8.00	Mandatory Improvement Required
7	Bad [Requires Major Portion of Pilot's Attention]	7.97	Bad Handling Qualities
8	Very Bad [Controllable Only with a Minimum of Cockpit Duties]	8.33 8.49	Very Bad Handling Qualities Completely Demanding of Pilot Attention, Skill or Effort
9	Dangerous [Aircraft Just Controllable with Complete Attention]	8.87	Requires Maximum Available Pilot Skill and Attention to Retain Control
(9-10)	(Won't Fly It)	9.00	Nearly Uncontrollable
10	Unflyable	10.00	Uncontrollable

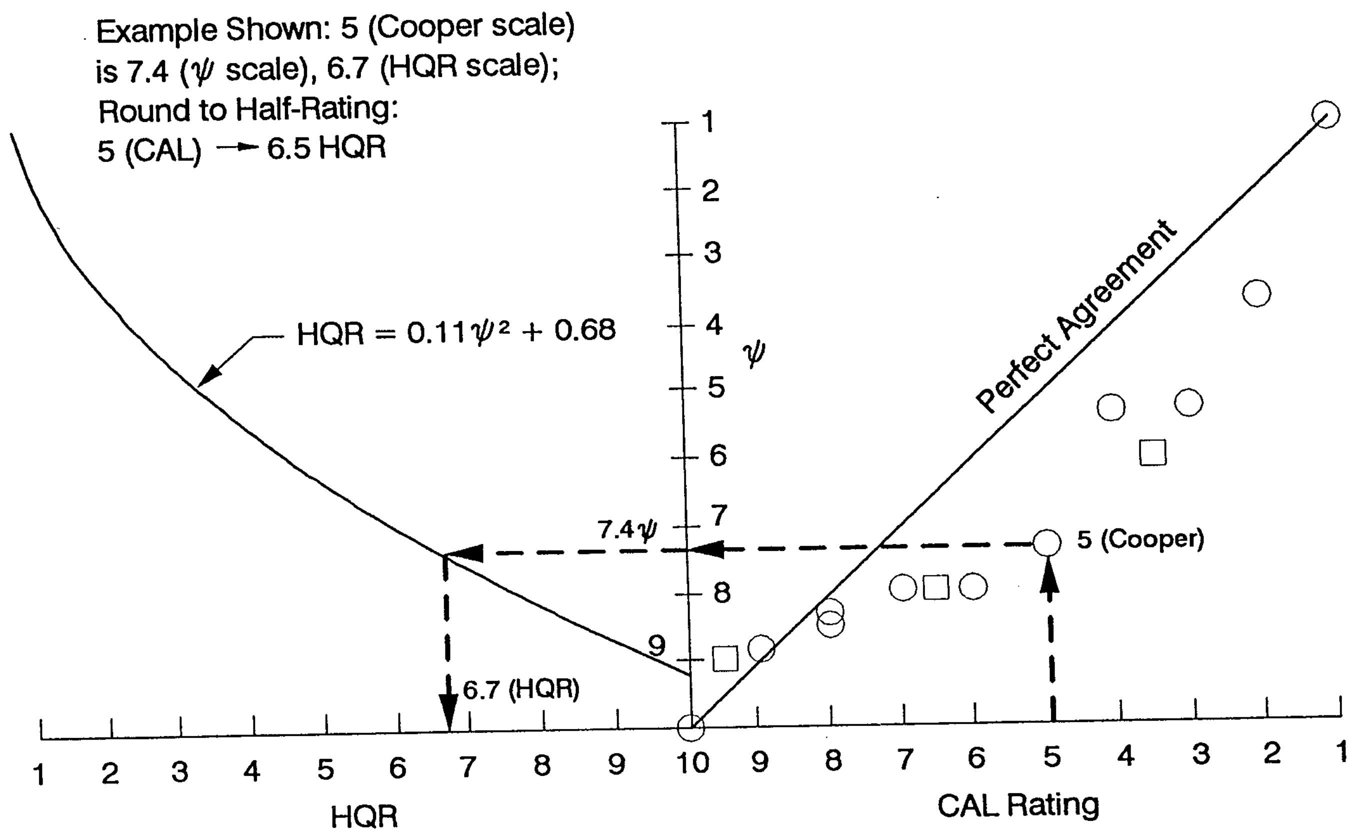


Figure E-12. Conversion of CAL Ratings to HQRs Through the ψ Scale

The nomographs allow us to go not only from the old scales to the HQR, but also back again. Hence, we can convert HQRs of 3.5, 6.5, and 9 to equivalent Cooper and CAL ratings to define the corresponding ratings for the flying qualities Levels. The following table summarizes the results of this exercise:

Level	HQR	Cooper	CAL
1	3.5	2.5	2.5-3
2	6.5	5.5	4.5-5
3	9	7.5	8.5

d. Summary

Figure E-13 summarizes the consequence of applying the nomographs of Figures E-11 and E-12. This figure shows the correspondence between the Cooper-Harper HQR scale ratings and ratings for the Cooper and CAL scales. There is an obvious offset in these ratings of about one rating point, with the exception of ratings below 3 and above 7. Thus, conversion from either of the older scales to the HQR scale requires the addition of about one rating to their values, e.g., a Cooper rating of 6 is roughly equivalent to an HQR of 7, etc. At the good end, ratings of 1 and 2, the ratings are equivalent; at the bad end, the CAL ratings tend to converge with, and the Cooper ratings diverge from, their HQR equivalents.

The conversion schemes introduced here should be applied any time an attempt is made to combine pilot ratings from disparate sources using any of these rating scales. It is clear that it is inappropriate to assume a commonality between numerical ratings from the Cooper, CAL, and HQR scales.

3. Analysis of Data

The definitions of τ_p, ω_{BW}, and Dropback are given in Section VI of this report. Phase Delay is not considered applicable to flight path response: ω_{BW_γ} crossplotted with ω_{BW_θ} is used to establish the flight path axis Bandwidth requirements. It is important to recognize that Dropback is not a stand-alone criterion. That is, there are systems that exhibit little to no adverse Dropback that are nearly uncontrollable due to, for example, lack of attitude Bandwidth. A system that is Level 1 in Bandwidth and Phase Delay, however, will receive Level 2 ratings if there is excessive Dropback. Therefore,

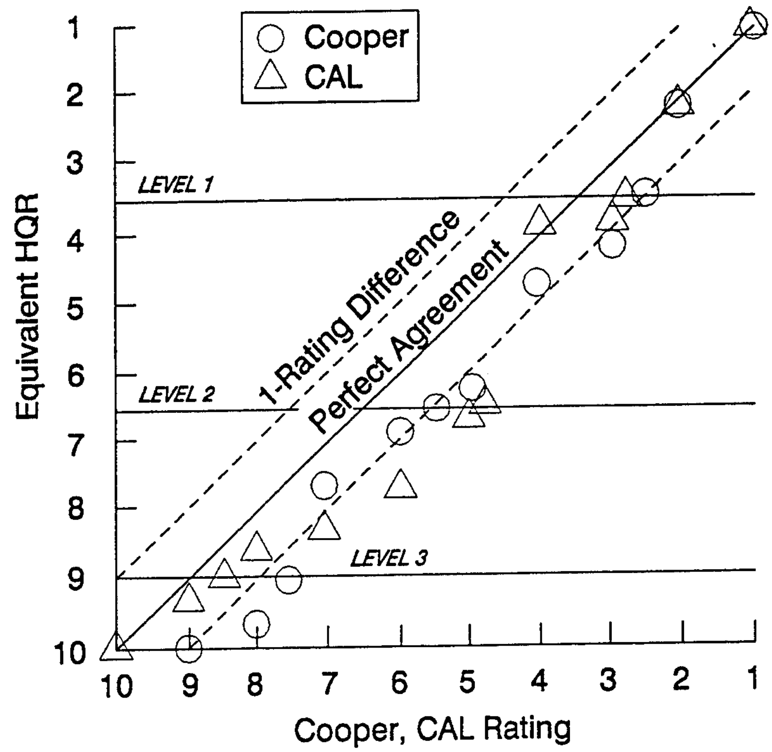


Figure E-13. Correspondence Between Cooper, CAL, and HQR Scale Pilot Ratings

Dropback is either acceptable or excessive (unacceptable); no distinctions between "Level 2 and Level 3 Dropback" are made, as they are in the Bandwidth requirements.

A classic limitation of the Dropback criterion is that it is applicable only to certain response-types: rate command, and some "rate-looking" conventional cases, notably those reduced to constant airspeed approximations.

a. <u>TIFS and Large Aircraft Data</u>

Plots of $\tau_{p\theta}$ vs. ω_{BW_θ}, ω_{BW_γ} vs. ω_{BW_θ}, and q_{peak}/q_{ss} vs. Drb/q_{ss} for the TIFS data are shown in Figures E-14 through E-16. The corresponding plots for the large aircraft data, with the same suggested Level 1 and Level 2 boundaries, appear in Figures E-17 through E-19. The identifiers used in the experiment, as well as the HQRs (or converted HQRs) for each configuration, are indicated, as is the general response-type. This final set of plots is the result of careful screening and iteration, as described below.

Pilot HQRs separated by a comma were given by the same pilot; a "/" indicates a change of pilots. For example "3,3,4/5/2" would mean that three different evaluation pilots rated the configuration, and one of them rated it three times. This raises the issue of how to weigh multiple ratings by a single pilot: it

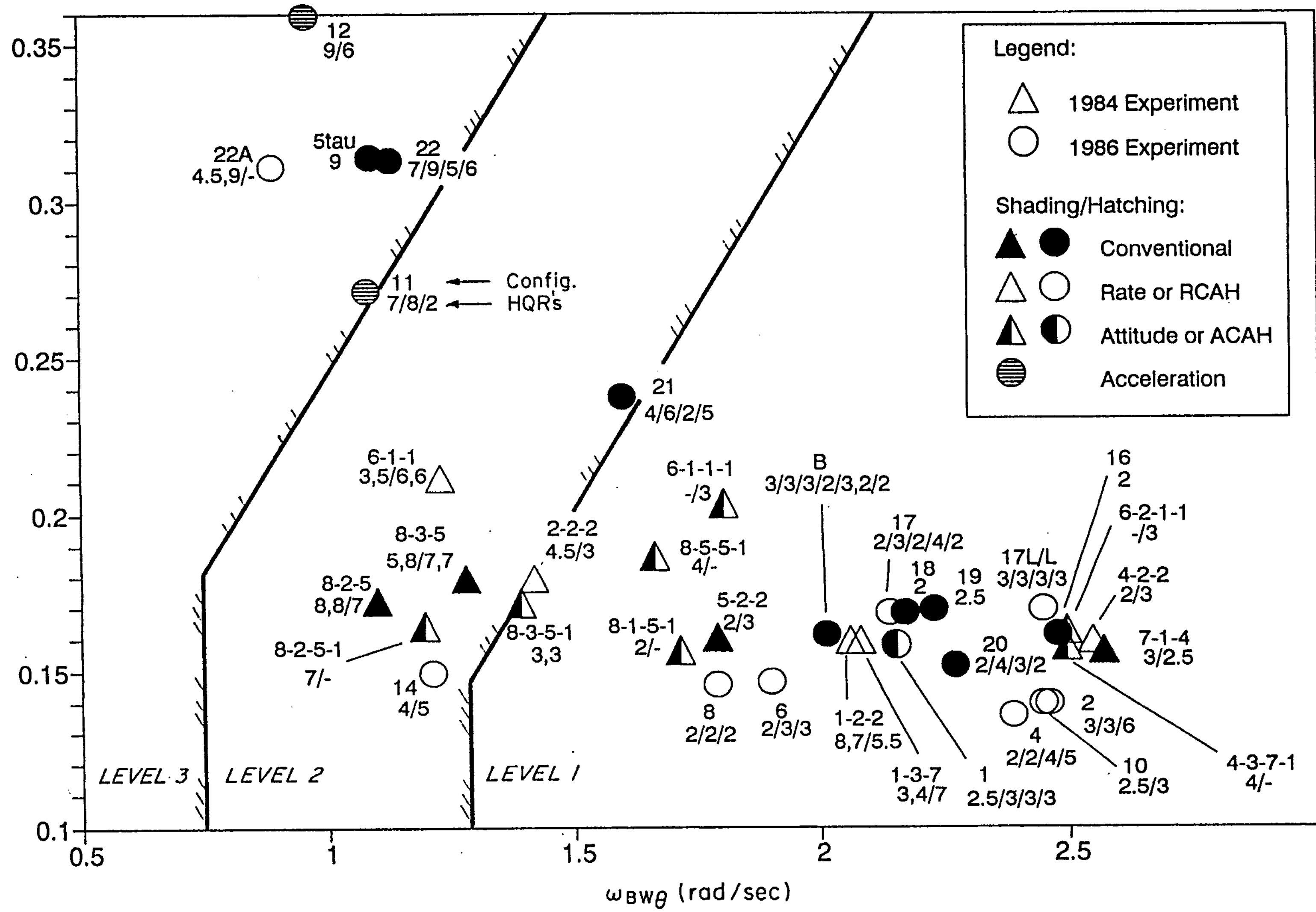


Figure E-14. Pitch Attitude Bandwidth *vs.* Phase Delay (TIFS Experiments)

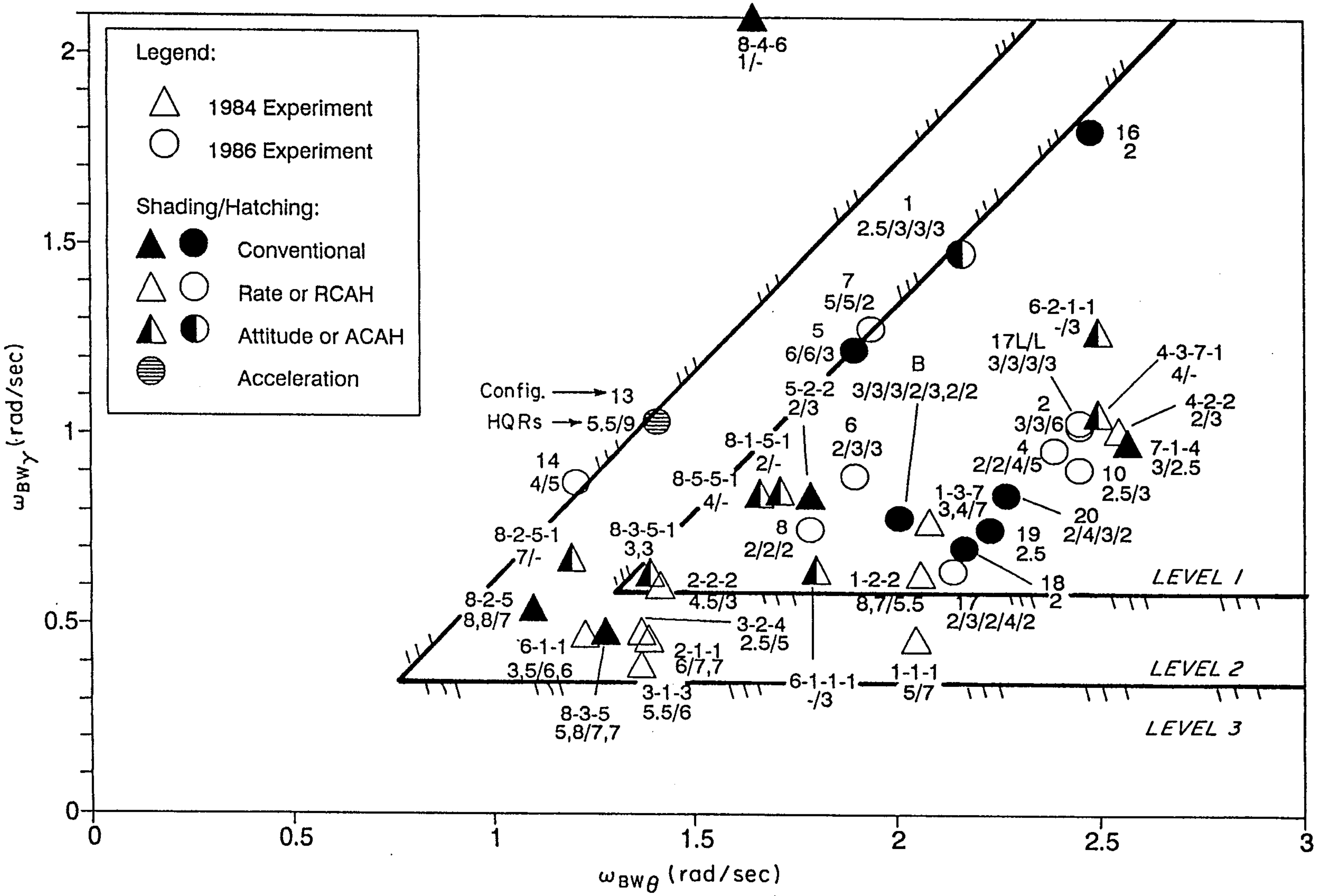


Figure E-15. Pitch Attitude Bandwidth *vs*. Flight Path Bandwidth (TIFS Experiments)

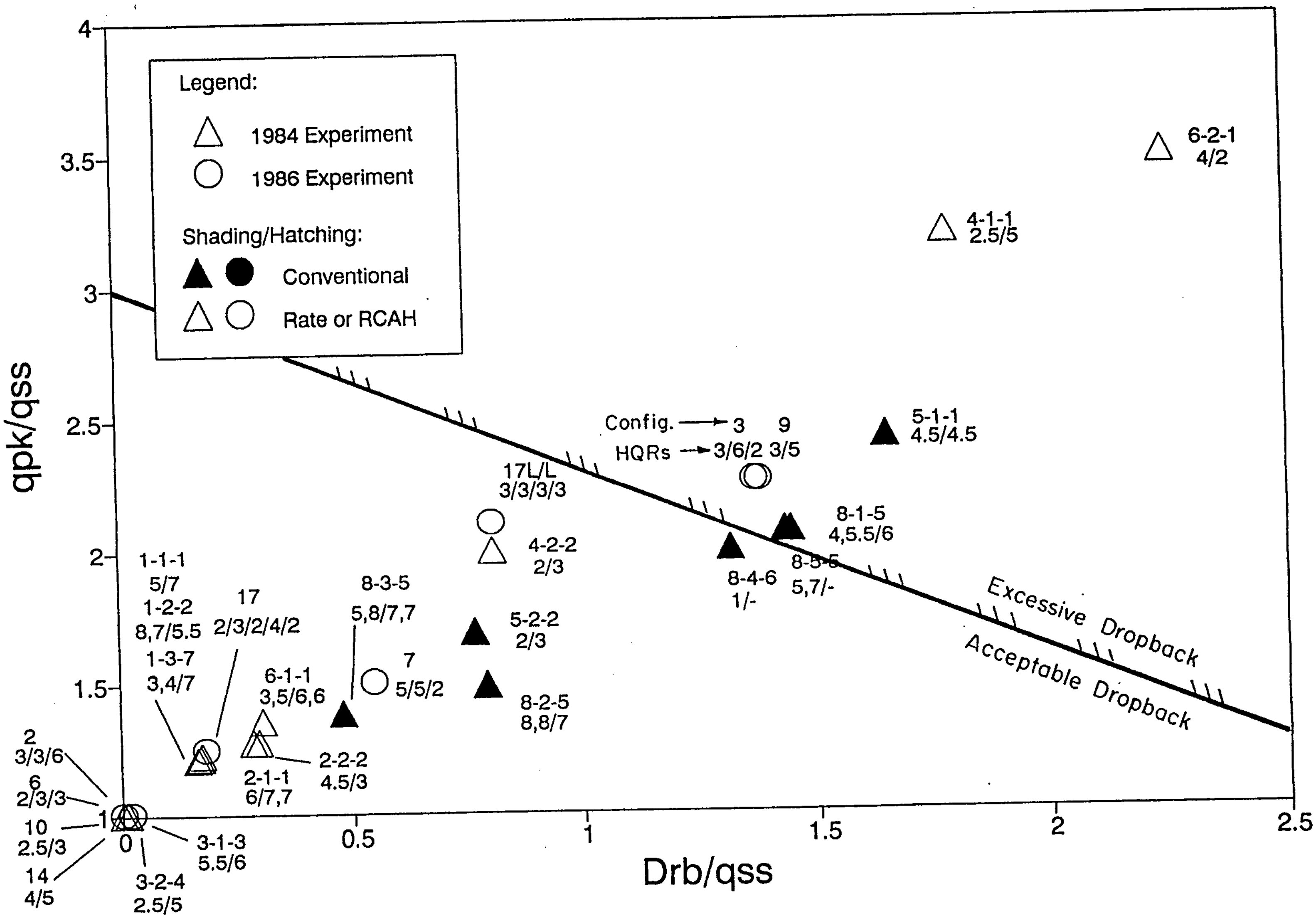


Figure E-16. Dropback (TIFS Experiments)

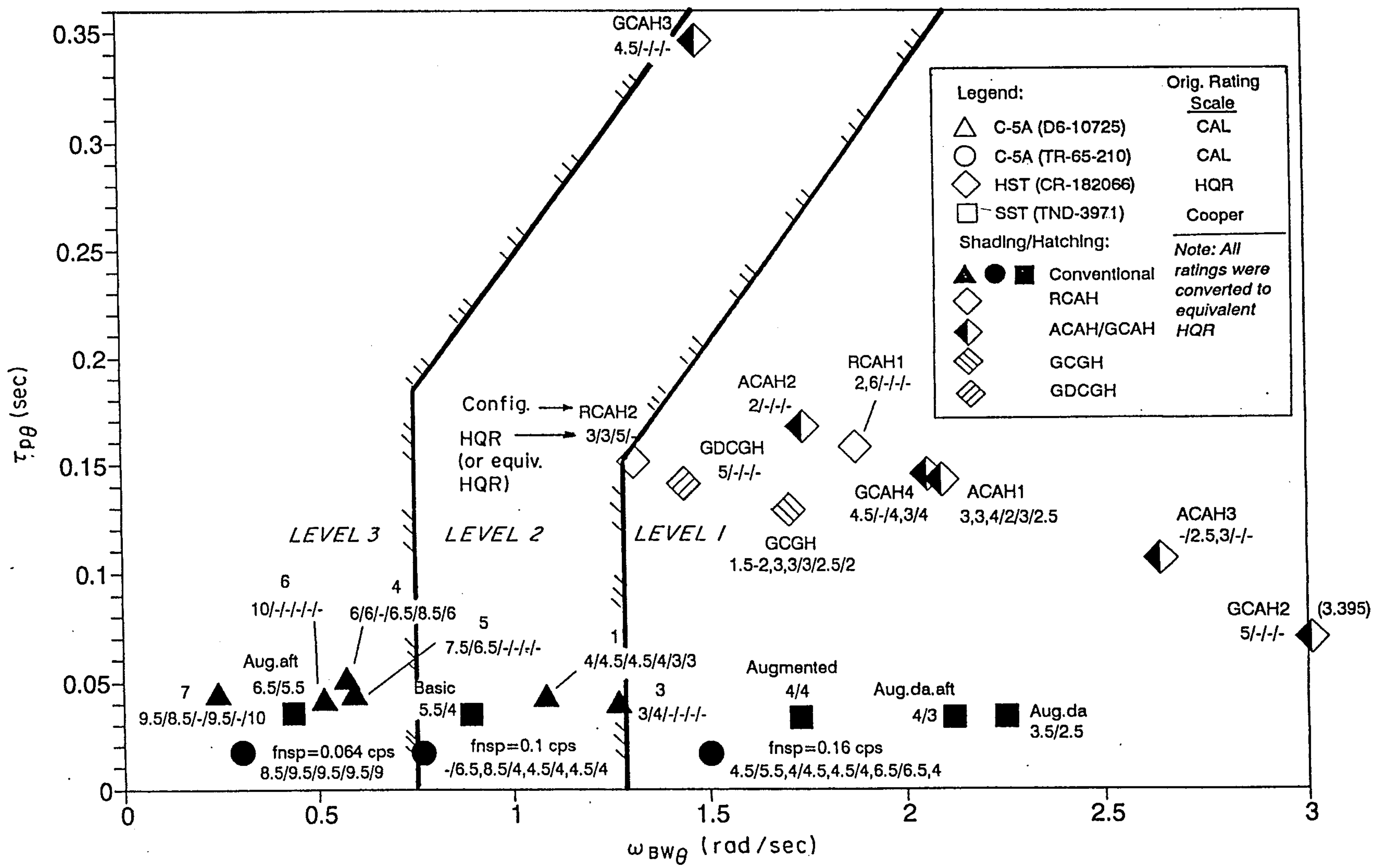


Figure E-17. Pitch Attitude Bandwidth *vs.* Phase Delay (Large Aircraft Data)

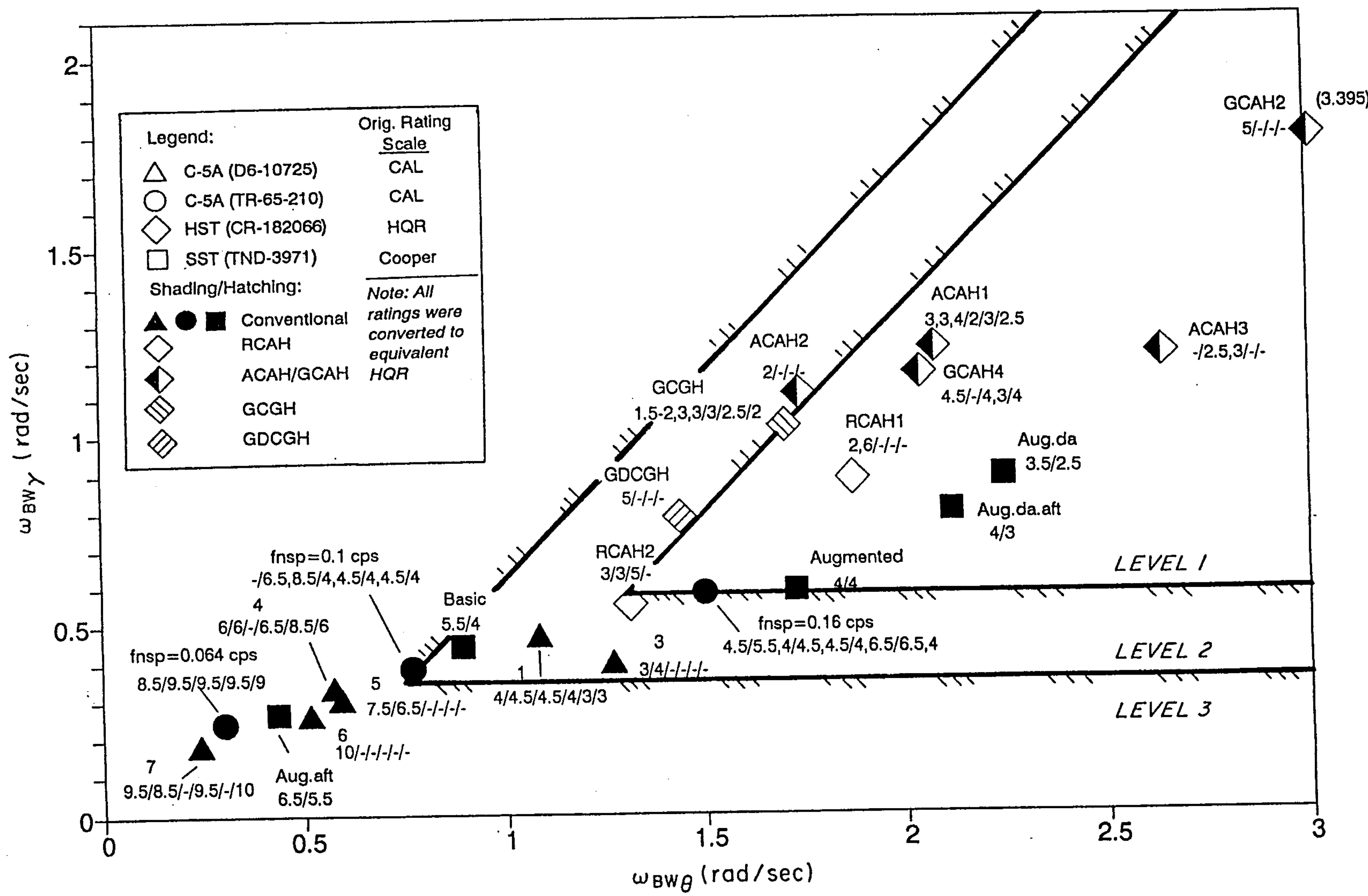


Figure E-18. Pitch Attitude Bandwidth vs. Flight Path Bandwidth (Large Aircraft Data)

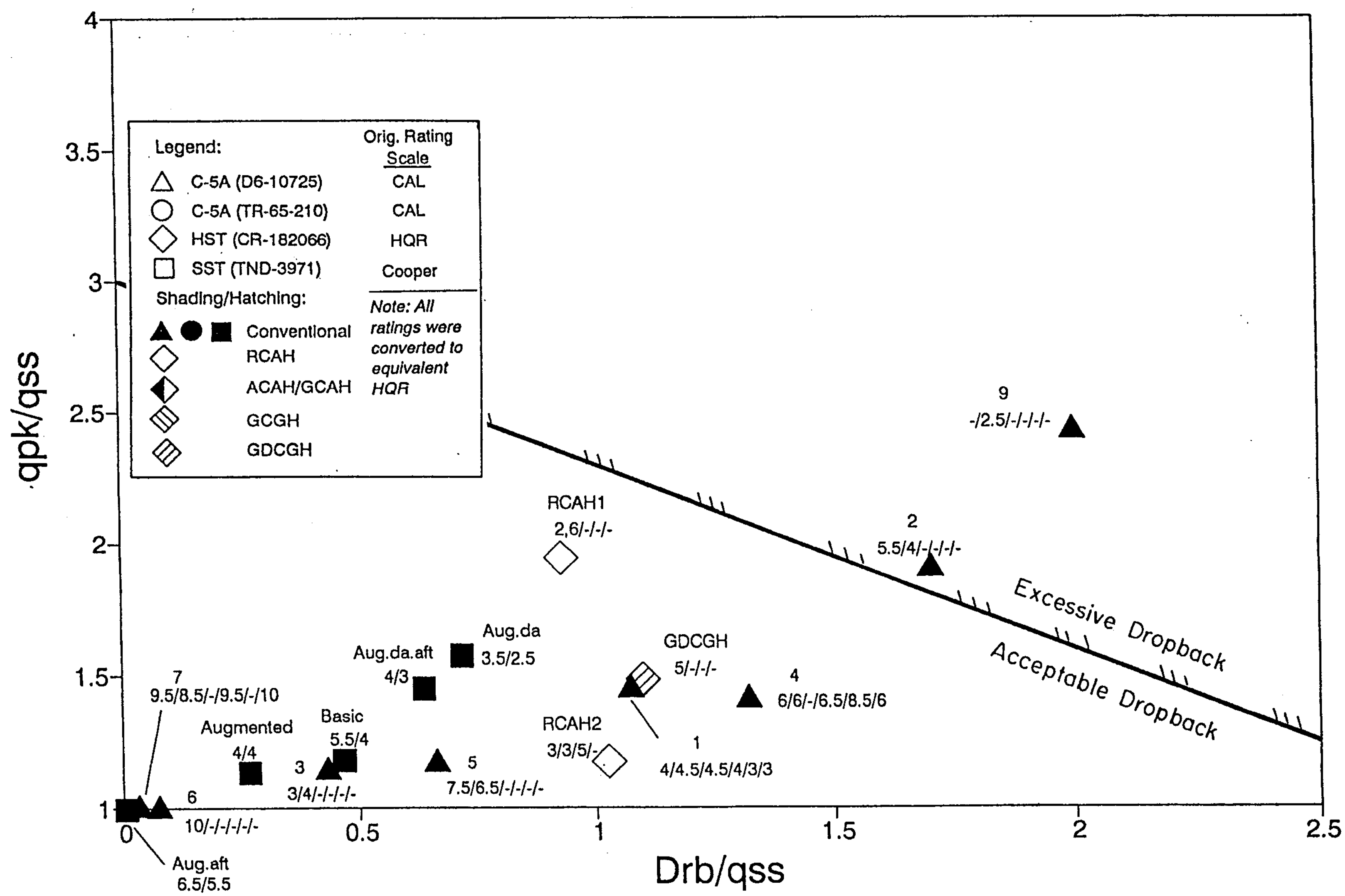


Figure E-19. Dropback (Large Aircraft Data)

might be argued that less significance should be attached to a set of ratings by a single pilot, as compared to a set of ratings from different pilots (for example, "2/2/2" could be a more reliable endorsement than "2,2,2"; and "3,3,3/5/6" might be treated as "3/5/6"). This was not done in this analysis; due to the lack of evidence of any pilot-specific trends in the data, it was assumed that the pilot freshly approached a configuration each time he rated it, and all ratings were given equal consideration. In addition, while the HQR scale is ordinal (Ref. E-13), and thus ratings should be measured in terms of medians rather than means, it is standard practice to average HQRs, as was done here for analysis. Consideration must still be given to the relative strengths of pilot ratings; for example, a configuration with ratings of 2, 3, and 6 has a Level 2 average (3.67) but a Level 1 median (3). Two of the three pilots judged it Level 1, however, so this case might best be considered Level 1 despite the Level 2 average rating.

As previously mentioned, the placement of the Phase Delay, attitude Bandwidth, and Dropback boundaries was primarily based on the TIFS data. The large aircraft (C-5A, HST, SST) data were considered as supporting information, and used to refine boundary locations where there were no TIFS cases for precise definition. Nevertheless, it will be shown that the degree of correlation of the large aircraft data with the recommended Bandwidth and Dropback requirements is comparable to that for the TIFS data.

There were many more points in the database than are shown *on any individual plot* in Figures E-14 through E-19. This is because an attempt was made to isolate and include only those points relevant to the definition of the boundaries for each plot. The exact procedure was as follows.

Most of the cases with response-types for which Dropback is appropriate — i.e., rate command and some conventional response-types — are included in Figures E-16 and E-19. The exceptions are those cases with high Phase Delay, defined here as $\tau_{p\theta} > 0.23$ sec. The excessive Dropback boundary provides a reasonable distinction between regions of average Level 1 and worse HQRs. Dropback is, to a greater extent than the frequency-domain criteria, dependent on pilot technique: some pilots find it less offensive than others. Thus, ratings like 2.5 and 5 are not uncommon for a single high-Dropback configuration. Many configurations that have negligible Dropback received Level 3 ratings for different reasons; these appear in Figures E-16 and E-19, and illustrate the shortcomings of Dropback alone in discriminating handling qualities.

Only points used to define the $\tau_{p\theta}$ vs. ω_{BW_θ} Level 1 and Level 2 boundaries are included in Figures E-14 and E-17. That is, points with excessive Dropback, and points that are not Level 1 due to excessively low or high ω_{BW_γ}, are not included in these plots, because the flying qualities of these configurations suffer for reasons unrelated to pitch attitude Bandwidth or Phase Delay. Similarly, points

with excessive Dropback, and points that have a $\tau_{p\theta}$ of about 0.23 sec or greater, are considered to have dominant characteristics other than flight path Bandwidth that affect the pilot ratings, and do not appear in Figures E-15 and E-18.

The interdependence of the data plots means that it was necessary to carefully screen each point and proceed through several iterations of plotting the data, evaluating the candidate boundary locations, and screening each point for special circumstances until it was felt that an optimal solution was reached in terms of matching the boundaries to the data. Note that the $\tau_{p\theta}$ vs. ω_{BW_θ} and ω_{BW_γ} vs. ω_{BW_θ} boundaries are not independent in the sense that the minimum allowable ω_{BW_θ} for Level 1 and Level 2 on each plot is the same.

Each configuration in this study was meticulously examined to see if the pilot rating(s) received could be explained by its position relative to the recommended boundaries on Figures E-14 through E-19. A configuration was considered a "hit" if:

- The average pilot rating (or single rating if only one was available) matched the Level of the region defined by the boundaries, or
- Conflicting, but adjacent, HQR Levels were given and the data point was near the appropriate Level boundary (e.g., a rating of 5/5/2 near the Level 1-2 boundary, or a rating of 5.5/9 near the Level 2-3 boundary).
- The pilot ratings indicated Level 3 and the configuration was in the Level 2 region on *both* the Phase Delay and γ-Bandwidth plots. A plausible explanation for this is the multi-axis flying qualities degradation phenomenon identified in Ref. E-19 and other sources. Essentially, deficiencies in both of two axes necessary for a task may combine to produce an HQR worse than the individual single-axis ratings.

A point was considered "marginal" if any of the following descriptions applied:

- The average pilot rating was within one-half point of being in the appropriate Level for the region (e.g., an average rating of 4 in Level 1).
- The average rating did not match the Level of the region defined by the boundaries, but a majority of the ratings matched the Level (e.g., a point rated 7/8/2 in the Level 3 region; average = 5.67 = Level 2, but two of the three pilots assigned ratings that are Level 3). This category is termed marginal by applying the median, rather than mean rating.

A point was considered a "miss" if:

- The HQRs were definitely inappropriate for the Level defined by the boundaries: not justifiable as "hit" or "marginal" by any of the above criteria.

Despite the apparent rigor in the above definitions, which evolved during the course of the investigation, a substantial amount of engineering judgement had to be applied. It would be very difficult to write a formal algorithm, for example, to place only the appropriate points on each plot, recognize what makes a particular pattern of pilot ratings significant, and identify the hits, misses, and marginals. It is felt that the application of the above principles resulted in a fair evaluation of how well the proposed boundaries explain the HQRs obtained in the experiments.

The overall results in terms of hits, marginals, and misses for the two major categories of data appear in Table E-3. A total of 79% of the cases resulted in hits, and 91% of all cases were at least marginal. This level of correlation is considered exemplary for handling qualities analysis, and a high level of confidence is expressed in these recommended requirements.

TABLE E-3. SUCCESS OF BOUNDARY PLACEMENT

Data Source	Total Points	Hits	Marginal	Misses
TIFS	51	41	6	4
Large Aircraft	26	20	3	3

b. Supplementary Aircraft Data

It is insightful to evaluate the proposed boundaries with respect to real-world aircraft. The plots in Figures E-20 to E-22 show ω_{BW_θ} vs. τ_{P_θ}, ω_{BW_θ} vs. ω_{BW_γ}, and Drb/q_{ss} vs. q_{peak}/q_{ss} for seventeen aircraft (or different configurations of the same aircraft), along with the suggested boundaries. The data here are taken from various sources (Refs. E-20 to E-25 and unpublished data), and are "force-referenced;" that is, the dynamics of the control feel system, if applicable, have been taken into account. An additional lag has been included to represent the elevator feel system lags.

Pilot ratings were available for only a few of the configurations, and appear on Figures E-20 to E-22. These ratings are averages, in cases where more than one pilot was involved. In some cases, the aircraft dynamics — from which Bandwidth, Phase Delay, and Dropback were computed — were drawn from a different source than that supplying the pilot rating(s), which is an additional reason to lower the credibility of these data compared to those presented above.

It is important to point out that there are no serious conflicts between the boundaries suggested in this analysis and the location of already-certified aircraft on the Bandwidth/Phase Delay/Dropback plots. The current FAR Part 25 does not require that certifiable aircraft have Level 1 flying qualities, just a level

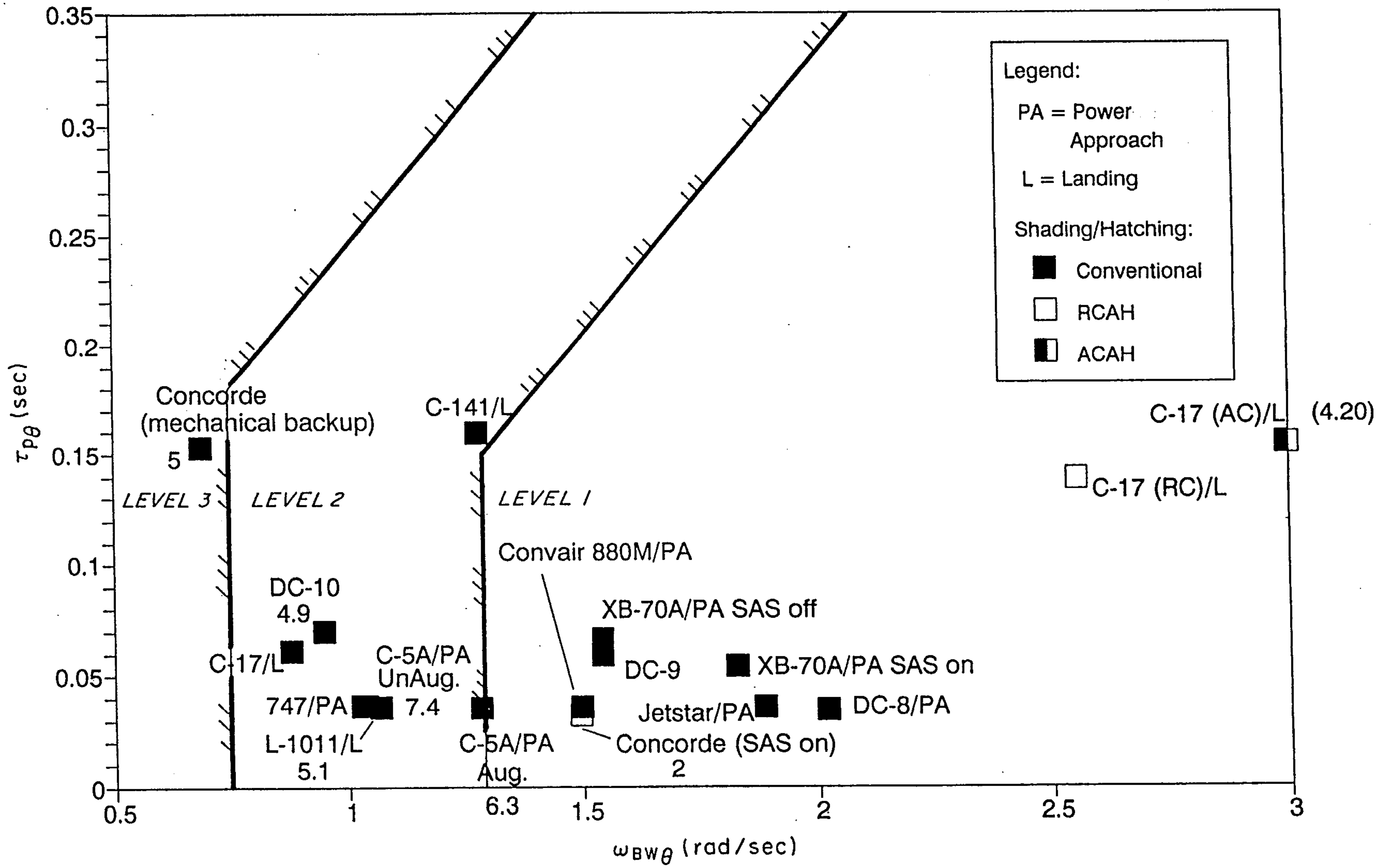


Figure E-20. Pitch Attitude Bandwidth vs. Phase Delay (Existing Transports)

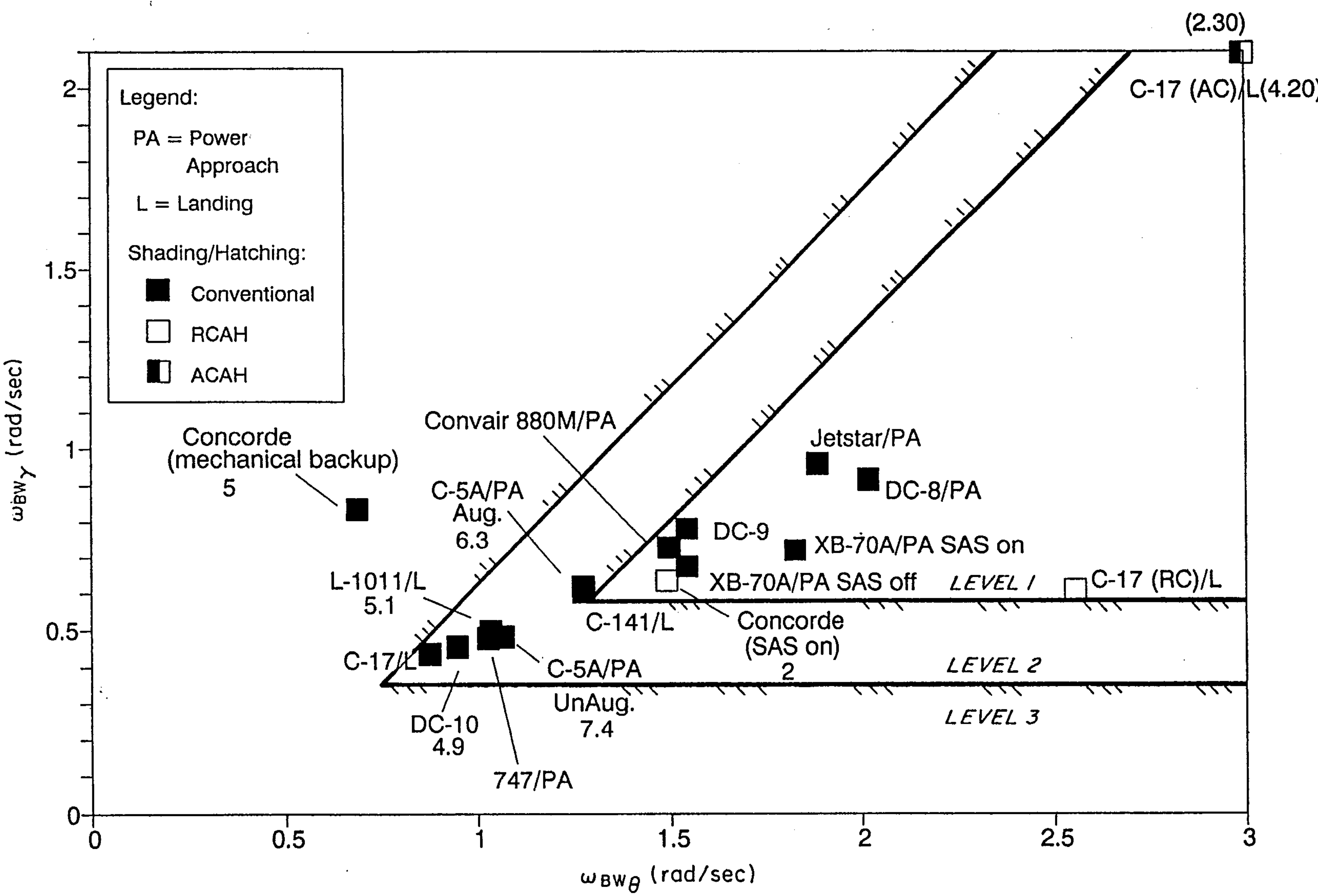


Figure E-21. Pitch Attitude Bandwidth *vs*. Flight Path Bandwidth (Existing Transports)

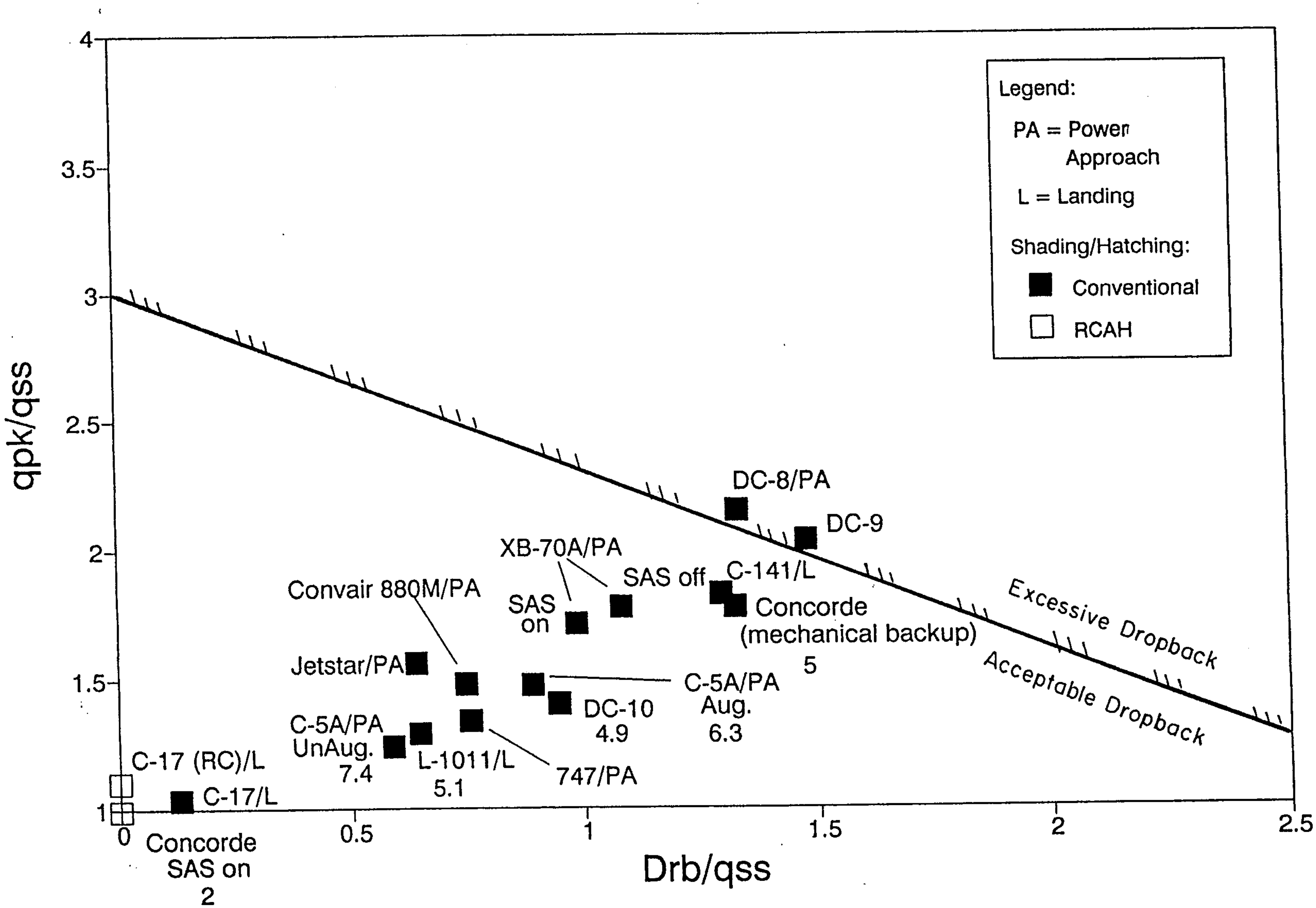


Figure E-22. Dropback Data (Existing Transports)

of safety of operation approximately equivalent to Level 2. Only one configuration is worse than Level 2 on these plots: the backup mechanical mode of the Concorde SST. This configuration received an HQR of 5, so it would be considered a "miss" by the standards listed above. Of the other data points with known HQRs, three would be considered "hits" and two (the two C-5A points) would be considered "marginal."

The evaluation tasks and general information for the aircraft that show pilot ratings in Figures E-20 to E-22 are presented next.

Concorde. — The pilot ratings attached to the "Concorde" data points in Figures E-20 to E-22 to are based on the approach and landing portion of the FAA flying qualities evaluation of the prototype aircraft (Ref. E-26). Twenty-five landings, most in VFR conditions, were performed by two evaluation pilots, who gave ratings on the Cooper-Harper HQR scale. The task was a standard approach (along a 3° ILS glideslope), flare and landing, with no supplementary tasks, or specific performance measures. Several configurations of the SAS and autothrottles were tested; the two ratings given here were for full augmentation (autothrottles on), and mechanical backup (no SAS or autothrottles). The latter mode exacted more pilot effort to compensate for the aircraft's slight longitudinal static instability.

The attitude and flight path dynamics of these two configurations were computed from Refs. E-24 and E-26; dropback was calculated using a constant airspeed approximation. The flare maneuver for this aircraft was noted in the flight tests to be unusual due to the abnormally strong ground effect the aircraft incurs, which produces a nose-down pitching moment in addition to a large increase in lift. The implication of this on piloting technique in Ref. E-26 was that the usual amount of pull force was required during flare, but, in contrast with most conventional aircraft, the aircraft exhibited little to no change in attitude during the final phase of the landing.

L-1011. — Reference E-27 describes a simulation of an L-1011 aircraft using the NASA Visual/Motion Simulator. Three pilots evaluated (using Cooper-Harper HQRs) configurations with moderate turbulence and no added time delay. The average rating of 5.1 indicated in Figures E-20 to E-22 is based on a task that consisted of a glideslope capture and approach, starting from 8 miles out at 2,000 ft altitude and 1,000 ft lateral offset. The following excerpt highlights two shortcomings of the Ref. E-27 data, as far as applicability to this analysis: "A few flares and touchdowns were attempted, but the pilots felt that this added nothing to the evaluation. The approaches were made on raw data displays." Therefore, the final, crucial phase of the task was omitted from the rating and high-fidelity visual cues were absent. The dynamics of the L-1011 configuration were computed from unpublished stability derivatives.

C-5A. — Like a portion of the C-5A data, Ref. E-28 was an in-flight simulation of the transport using a variable stability B-26. This experiment incorporated the final version of the C-5A dynamics and flight control system design, described in Ref. E-20. The powered approach task in this case consisted simply of capturing the ILS localizer and tracking the glideslope to the flare point (although one test run reportedly included a lateral offset). The flare and touchdown were not taken into account in the evaluation, but the lateral-directional characteristics were.

The pilot ratings shown here are for configurations with 1) all augmentation on (average 6.3), and 2) only the lateral-directional SAS on (longitudinally unaugmented, average of 7.4). In both cases, the stick force/g was varied, and the ratings shown are for the best setting. The ratings were originally given by the three pilots using the CAL rating scale; these ratings have been converted to Cooper-Harper HQRs and averaged.

DC-10. — The dynamic model from which the DC-10 characteristics in Figures E-20 to E-22 were calculated, as well as the HQR indicated, is from Ref. E-22 — a 6-DOF motion-based simulation at Douglas Aircraft Company. The rating shown was for longitudinal axis control, with simulated turbulence on, with the baseline configuration (a linearized set of wide-body jet equations of motion). The Cooper-Harper HQR scale was used. The task, a simple ILS glideslope capture and approach, was performed by four pilots. As was the case for the C-5A and L-1011 data above, flare and landing were not part of this experiment.

D. DEVELOPMENT OF BANDWIDTH AND DROPBACK REQUIREMENTS FOR FIGHTERS (CLASS IV) FOR UP-AND-AWAY TRACKING (CATEGORY A)

The valid data base for this set of requirements is the familiar Neal-Smith experiment (Ref. E-4). This experiment is described in detail in Section VI of the report in support of the development of PIO requirements.

The Neal-Smith data were analyzed by plotting the configurations on plots of pitch attitude Bandwidth, flight path Bandwidth, and Dropback, as presented in figures E-23 through E-25. Figures E-23 and E-25 include all cases; for figure E-24, only those cases with relatively low Phase Delay (less than 0.10 sec) and acceptable Dropback are shown. These figures form the basis for the proposed requirements in the report. As with all of the requirements in the main text, the feel system has been included for calculation of the parameters, even though this experiment used force commands. The addition of Dropback as a requirement, along with the inclusion of the feel system, has resulted in pitch attitude Bandwidth limits that are well below those published in MIL-STD-1797A: the Level 1 limit, for example,

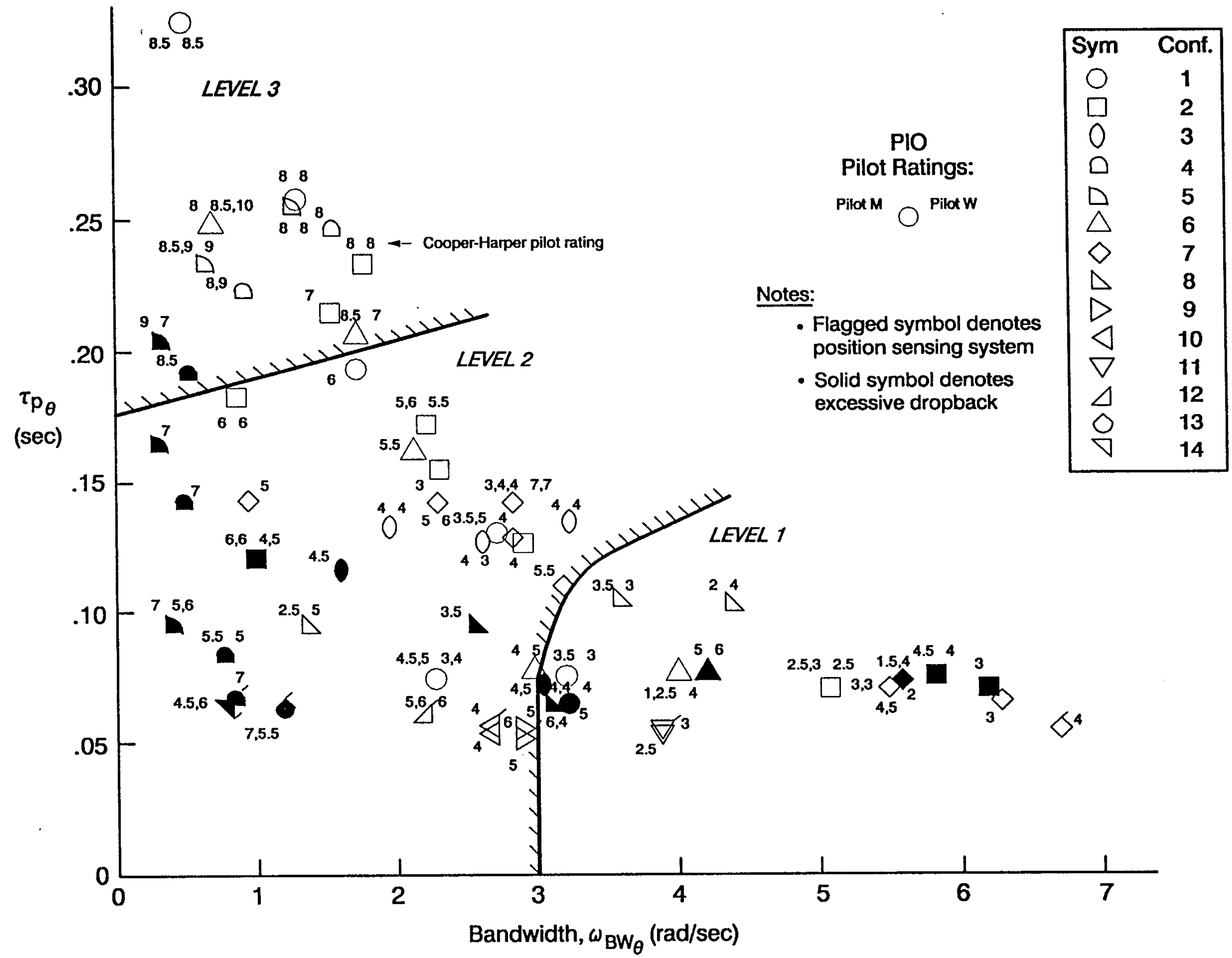


Figure E-23. Neal-Smith Data on Pitch Attitude Bandwidth Boundaries

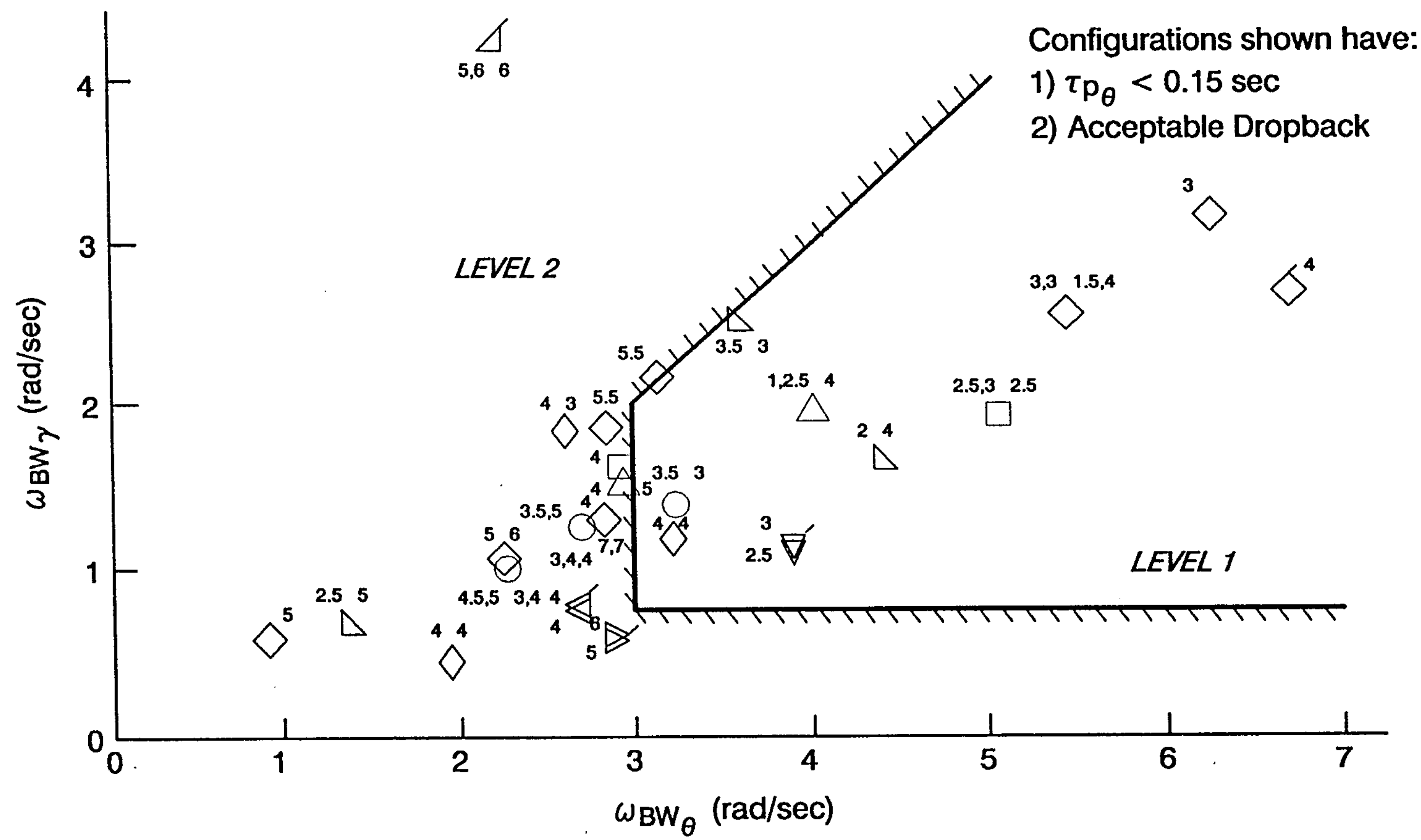


Figure E-24. Flight Path Bandwidth *vs*. Pitch Attitude Bandwidth for Selected Neal-Smith Configurations

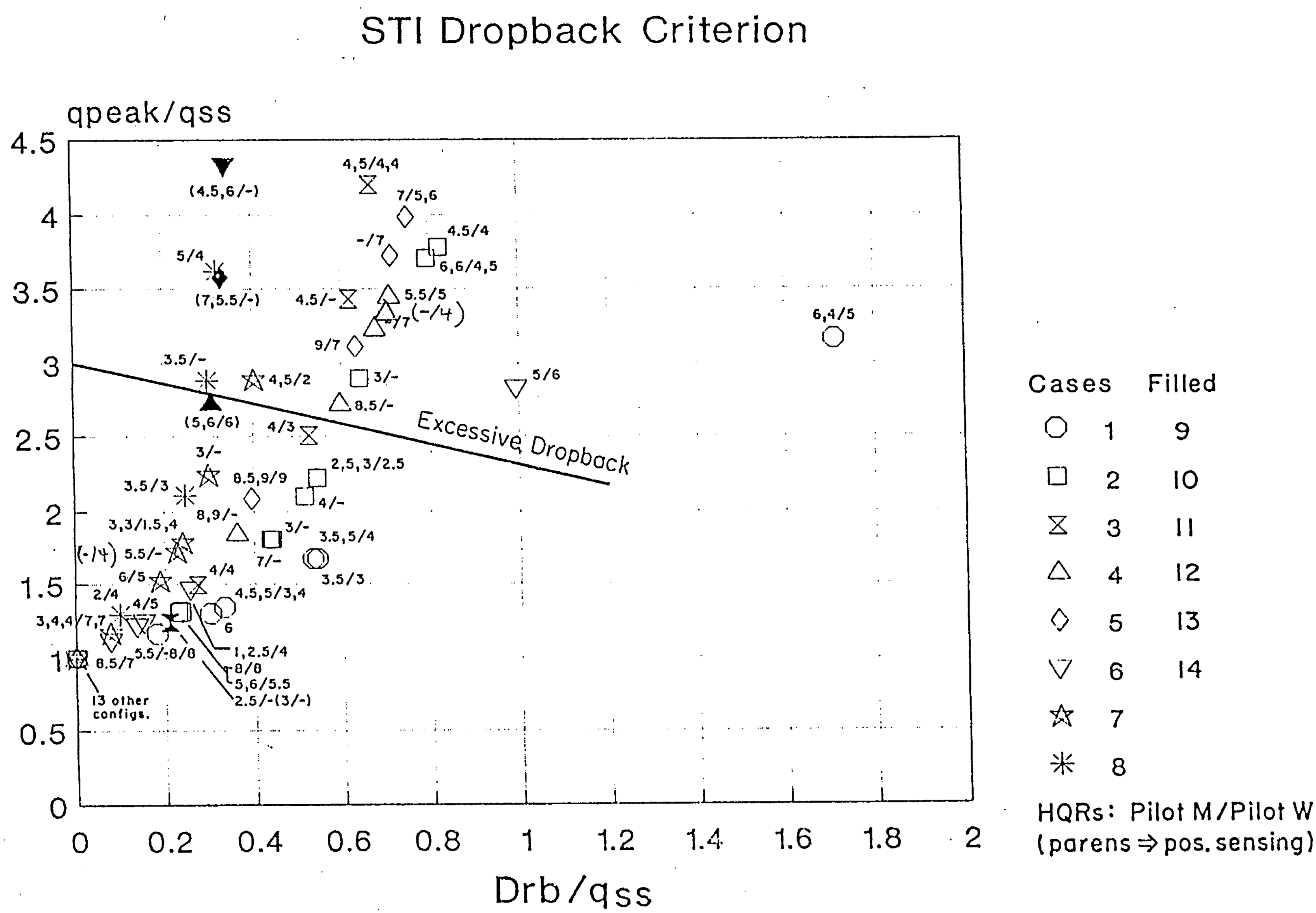


Figure E-25. Dropback Characteristics of Neal-Smith Data

has dropped from 6.5 to 3 rad/sec. There is not strong support for the flight path Bandwidth limits of figure E-24. These limits are drawn to be consistent with the Category C boundaries, discussed below.

The proposed requirements correlate the Neal-Smith data extremely well: with one exception, every case in the Level 1 region on pitch attitude Bandwidth that is not Level 1 fails either the flight path Bandwidth or Dropback requirement. The single exception is a case rated a 4 by one pilot. Similarly, there is only one case with a Level 1 rating in the Level 2 region in figure E-23 (a configuration rated a 3 by one pilot), and all Level 3 cases are correctly explained by either Phase Delay or Dropback.

The combined requirements correctly correlate 57 of the 62 Neal-Smith configurations. This is an excellent rate. The five cases not correctly correlated were 7P and 2F (mentioned above); 2C (rated a 3 by Pilot M, predicted Level 2 by Dropback); and 13 and 14 (both of which should be Level 3 based on a combination of Level 2 pitch attitude Bandwidths and excessive Dropback; these cases were rated 7 and 5.5 (case 13), and 4.5 and 6 (case 14), by Pilot M).

E. DEVELOPMENT OF BANDWIDTH AND DROPBACK REQUIREMENTS FOR FIGHTERS (CLASS IV) FOR PRECISION LANDING (CATEGORY C)

For this set of proposed requirements the LAHOS (Ref. E-5) data were used. The data are shown in Figures E-26 through E-28. The pitch attitude Bandwidth and Dropback requirements are well supported by the data. Flight path Bandwidth (Figure E-27) is not, however, due primarily to a lack of data. The boundaries drawn are, in fact, based on only a single point (the case with an HQR of 6); they were sketched to resemble the limits for transports discussed above. A single case does not seem to be strong support for the lower limit as sketched. More data are clearly needed.

F. REVIEW OF THE SMITH-GEDDES PIO CRITERIA AND DEVELOPMENT OF BANDWIDTH-BASED PIO REQUIREMENTS

1. *Data Sources*

Flight research data for both fighters and transports were compared with the Smith-Geddes and Bandwidth criteria. Every effort was made to apply both HQRs and PIORs. For those studies where PIORs were not obtained, only HQRs have been used.

In some references the occurrence of PIOs is specifically noted and PIO frequencies are reported. According to the Smith-Geddes criteria, if a PIO occurs it is most likely to be at the frequency ω_c. The effectiveness of this prediction is tested using the flight research data.

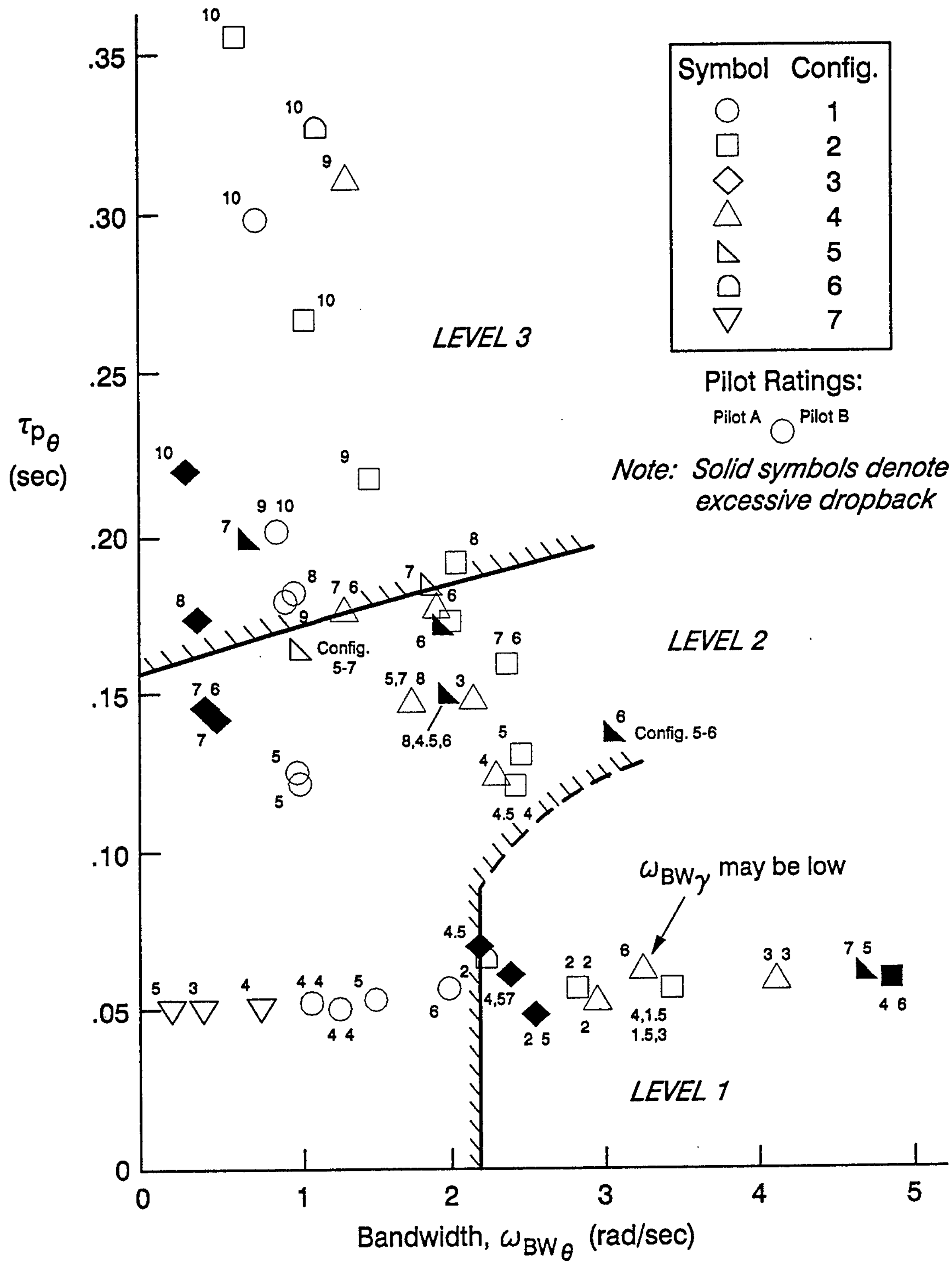


Figure E-26. LAHOS Data on Pitch Attitude Bandwidth Boundaries

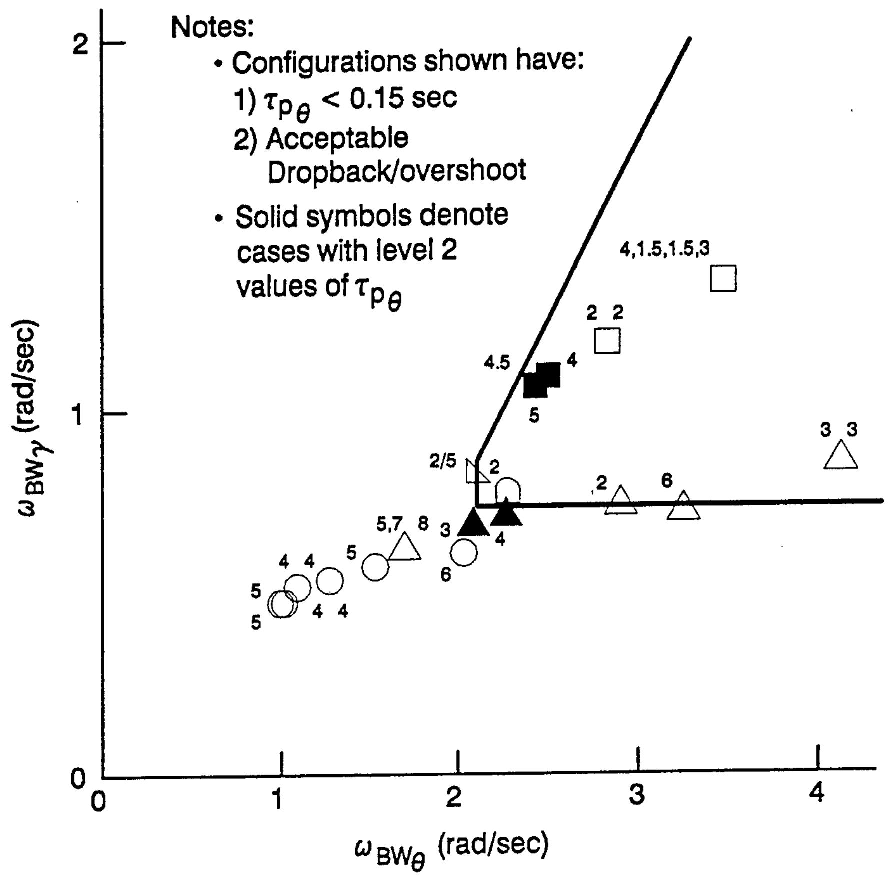


Figure E-27. Flight Path Bandwidth *vs.* Pitch Attitude Bandwidth for Selected LAHOS Configuration

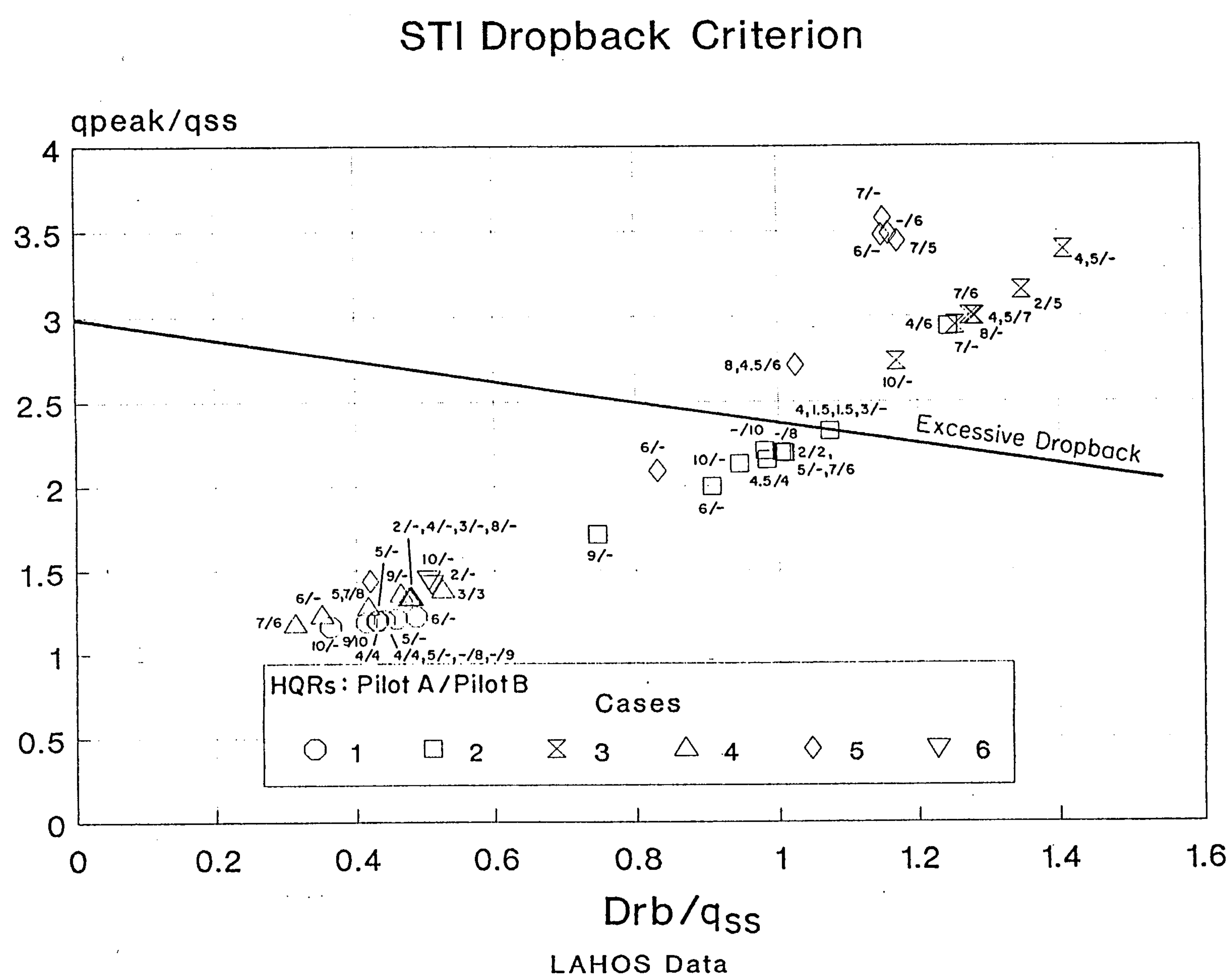


Figure E-28. Dropback Characteristics of LAHOS Data (Class 7-1, 7-2, 7-3 — unstable, not shown)

2. Review of the Smith-Geddes Criteria

a. Definitions

The following is a very brief review of the parameters of the Smith-Geddes criteria. It is assumed that the reader is familiar with the hypotheses behind the criteria.

The Smith-Geddes criteria are defined in Ref. E-29 and summarized in Figure E-29. The initial development of these criteria followed fundamental pilot-vehicle modeling rules, as documented in Ref. E-30. Application of the criteria required closed-loop analysis using a simple pilot model, with an outcome of an expected attitude phase margin at the predicted crossover frequency. The selection of pilot model forms and crossover frequencies was not clearly called out; such analysis is almost an art form, as the user must carefully determine the most likely form of pilot model from existing rules (e.g., Ref. E-30) and then decide on the requirements for a reasonable closed-loop response. As such, the initial Smith-Geddes criteria were unwieldy and were certainly not in a form amenable to incorporation into a military flying qualities specification format. As the criteria evolved (e.g., Refs. E-31, E-32, and E-33), a set of rules was established that requires only the aircraft-alone frequency response of pitch or roll attitude to stick force.

The parameters of the Smith-Geddes criteria are as follows:

- Slope of the pitch attitude-to-stick force transfer function, S, defined between 1 and 6 rad/sec, in units of dB/octave. For Level 1 handling qualities, $S \leq -2$ dB/oct. No limit is given for Level 2.

- Criterion frequency, ω_c, defined as $6 + 0.24S$. No handling qualities limits are placed on ω_c, but if a PIO is predicted this is the expected PIO frequency.

- Phase angle of the θ/F_{es} transfer function measured at ω_c. For Level 1, $\angle\theta/F_{es}(j\omega_c) \geq -123$ deg; this limit may be relaxed to -130 deg depending upon the value of the normal-acceleration parameter defined next (see Figure E-29). The Level 2 limit is -148 deg, or -165 deg depending upon normal acceleration response (Figure E-29).

- If the phase angle $\angle\theta/F_{es}(j\omega_c)$ is more negative than -180 deg, PIO is predicted. If the phase is between -165 and -180 deg, PIO is predicted if, in addition, the normal acceleration response at the pilot's station is such that $\Phi(j\omega_c) = \angle n_{z_p}/F_{es}(j\omega_c) - 14.3\omega_c \leq -180$ deg. In other words, given no phase margin in pitch attitude at the criterion frequency, the aircraft is definitely susceptible to PIOs; if there is 15 deg or less phase margin, PIO will occur if there is no phase margin in adjusted normal acceleration.

- Rise time of the step response of pitch rate, t_q, defined as the time to first peak or, if there is no peak, time to 90% of steady state response. For Level 1, $0.2 \leq t_q \leq 0.9$ sec. There is no Level 2 limit.

- For θ/F_{es} (Applies to ϕ/F_{as} Also), Define:

  S = Slope of $|\theta/F_{es}|$ for 1–6 rad/sec, dB/octave

  ω_c = Criterion Frequency = $6 + 0.24S$, rad/sec

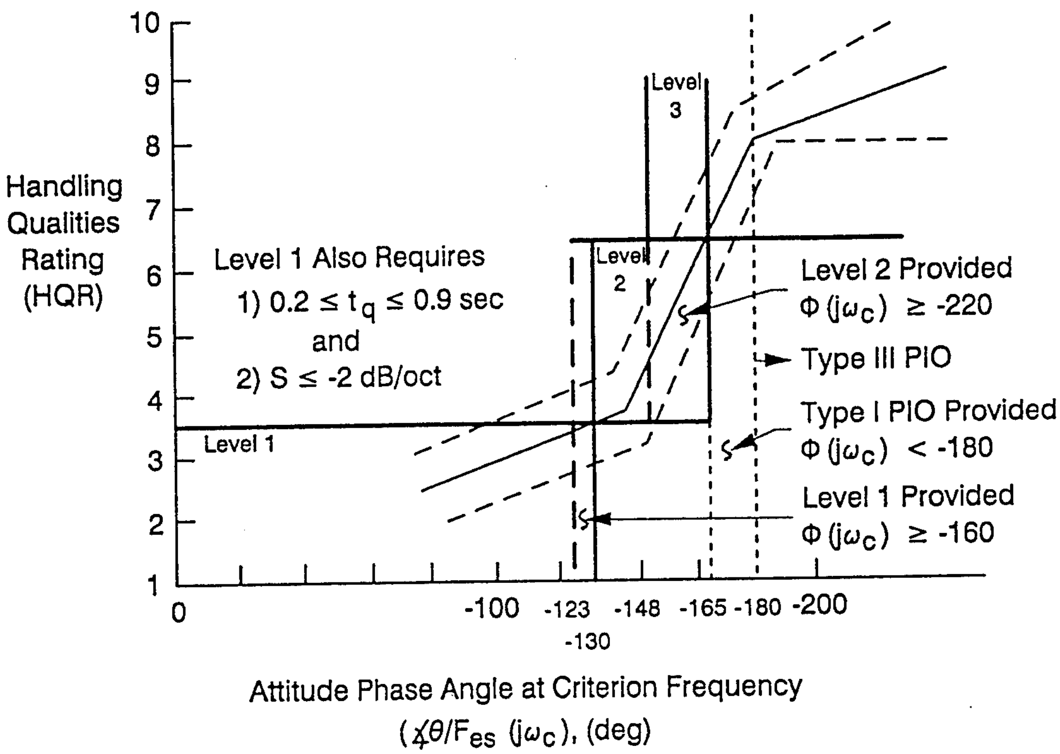
  $\measuredangle \dfrac{\theta}{F_{es}} (j\omega_c)$ = Attitude Phase Angle at Criterion Frequency, deg

  t_q = Time to Peak Pitch Rate From Step Response (90% of steady state if no peak), sec

- For θ/F_{es} only, Define:

  $\Phi (j\omega_c)$ = Normal Accel Phase Parameter = $\measuredangle \dfrac{n_{zp}}{F_{es}} (j\omega_c) - 14.3\omega_c$, deg

a) Parameters



b) Requirements

Figure E-29. Smith-Geddes Criteria (Pitch Shown; Roll Identical Except There is no Equivalent to $\Phi(j\omega_c)$)

b. Data for Fighter Aircraft: Up-and-Away (Category A) Pitch Tracking

It is appropriate to start here, since the Smith-Geddes criteria were originally developed using flight data for this task. There is only one well-documented flight experiment for pitch tracking: the Neal-Smith experiment, Ref. E-4, discussed earlier in this appendix. (There are a number of other references for pitch tracking, but all suffer from some deficiency; most were performed before the advent of the Cooper-Harper Handling Qualities Rating scale, performance limits were not clearly defined, pilot comments — especially indicating PIO tendency — are not published, etc. These references are not considered here.)

The Neal-Smith data have been used to develop many handling-qualities criteria; of the six alternative pitch response criteria in MIL-STD-1797A, only one — the traditional "CAP" criteria — is not based to some extent on the Neal-Smith data. In addition, the Smith-Geddes PIO and handling qualities criteria were generated from this data base (Refs. E-31 and E-32).

In the Neal-Smith experiment, 57 different combinations of short-period dynamics and added lead-lag elements were evaluated in up-and-away, fighter-type pitch tracking tasks. Fifty-one of the configurations used force commands and six used position commands. There are five more evaluations that may be considered as separate evaluations, although it is not common to do so. Two of these were cases designed for the force-sensing portion, but flown with position sensing instead (cases 4P and 7P). The other three were cases designed to be flown with *position* sensing, but flown with *force* sensing instead (variations of cases 9, 10, and 11). Since there is nothing inherently "wrong" with these five additional cases, they are considered to be configurations for this analysis, resulting in a total of 62 different sets of dynamics. To differentiate the three force-sensing variations of cases 9, 10, and 11 in this discussion, they are labeled as 9(f), 10(f), and 11(f).

The test aircraft was the USAF variable stability NT-33A. Both HQRs and PIORs were given by one or both of two evaluation pilots. The Neal-Smith data have been analyzed extensively; several of the configurations exhibit unusual, non-conventional response forms (e.g., Ref. E-10) that have confounded many of the criteria developed both prior to, and directly from, the Neal-Smith data.

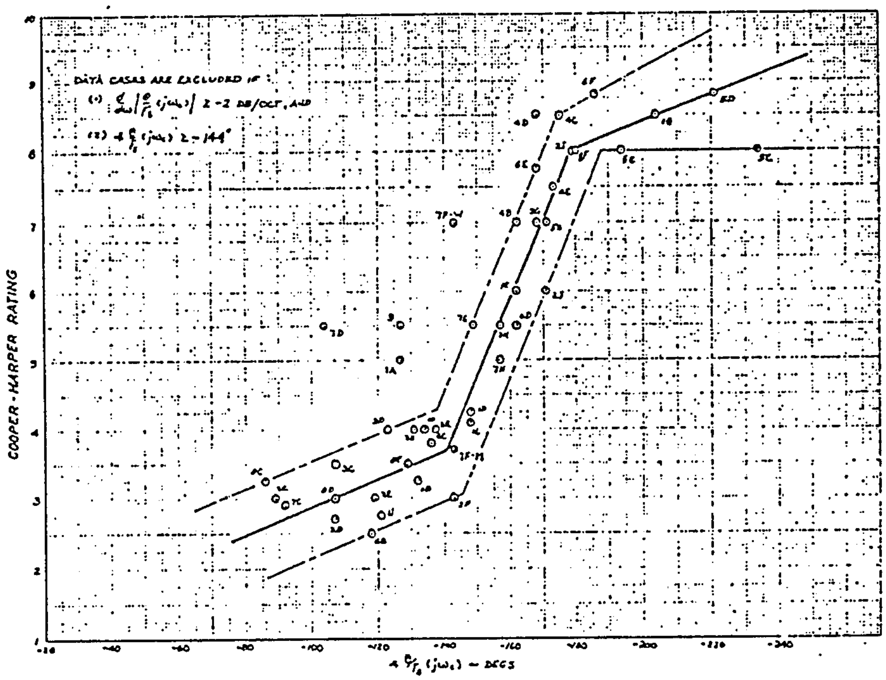
For force-sensing cases, for any criteria that are defined based on response to controller force inputs the feel system is not included as a part of the effective vehicle dynamics. Based on the analysis of Ref. E-24, it may be more appropriate to *always* consider the force-feel system in analysis, regardless of the mechanization. In the case of the Neal-Smith experiment, however, this is almost a moot issue, since a very fast feel system was used (stick natural frequency of 31 rad/sec) so it would make little difference

in any calculations. For this analysis the traditional approach has been taken: the Smith-Geddes criteria are defined for force inputs, so the feel system is ignored for force sensing and included for position sensing.

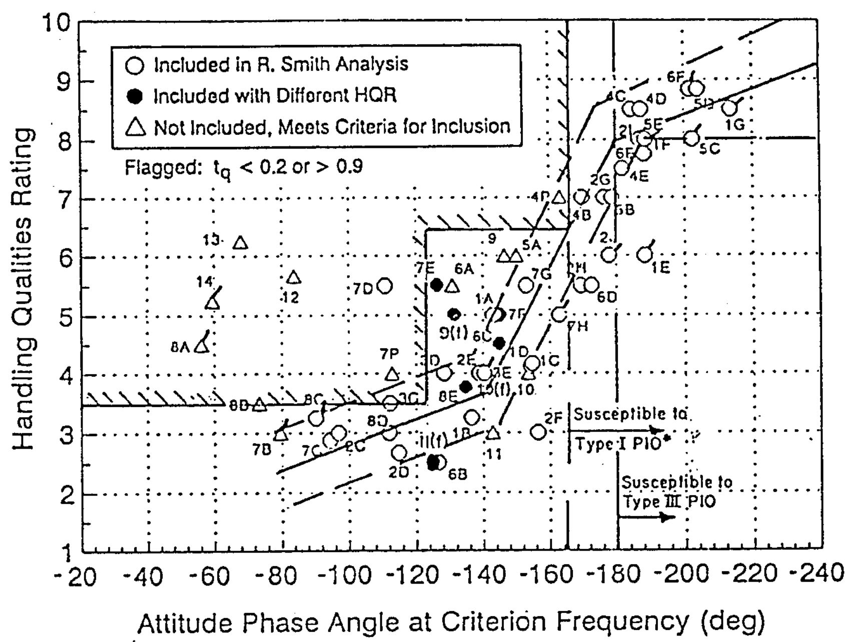
Handling Qualities Ratings. — Figure E-30 shows average HQRs from the Neal-Smith experiment plotted against pitch attitude phase angle at the criterion frequency. Figure E-30a is a reproduction of the original figure from Ref. E-32 upon which the Smith-Geddes criteria are founded. Not all of the Neal-Smith cases are on this plot, as the legend indicates. First, Smith and Geddes did not evaluate two of the position-sensing cases at all (cases identified in Ref. E-4 as 4P and 7P). Second, for the three cases that were flown with both force and position sensing (9, 10, and 11), the ratings for both sensing types were lumped together. Thus, even though the criteria are defined in terms of control force, the feel system was ignored for the three position-sensing cases. In addition, 14 cases were excluded from Figure E-30a because they exhibited other characteristic deficiencies. The 14 cases excluded by Smith and Geddes were those that simultaneously failed the phase slope requirement (i.e., had $S \geq -2$ dB/oct) *and* exhibited low phase angle at the criterion frequency (i.e., had $\angle\theta/F_{es}(j\omega_c) \geq -144$ deg). The reasons for this exclusion are discussed in Ref. E-32. As a result, of the 62 possible cases, there are 43 represented on Figure E-30a (44 points are shown: the pilot ratings for configuration 7F are shown separately for the two evaluation pilots). Specifically, the cases not shown on Figure 3a are 2A, 2B, 3A, 3B, 4A, 5A, 6A, 7A, 7B, 8A, 8B, 12, 13, and 14 (excluded by Smith and Geddes); 4P and 7P (not analyzed), and 9, 10, and 11 (all included with 9(f), 10(f), and 11(f)).

The Smith-Geddes parameters were recomputed for all 62 of the Neal-Smith configurations, resulting in the data plot of Figure E-30b. For comparison, the cases that met the Figure E-30a criteria for exclusion have been left off of this figure as well. Cases represented by triangles in Figure E-30b are the two position-sensing cases not analyzed by Smith and Geddes (4P and 7P); the position-sensing cases that were analyzed but now have the feel system included (9, 10, and 11); and cases that, in the reanalysis, do not fail the criterion applied for Figure E-30a (5A, 6A, 7B, 8A, 8B, 12, 13, and 14). As a result, where Smith and Geddes analyzed 44 cases, a total of 56 appear on Figure E-30b. The six cases not plotted are 2A, 2B, 3A, 3B, 4A, and 7A.

Five cases (solid symbols on Figure E-30b) also have different average HQRs from those used in Ref. E-32. In one case, individual ratings were plotted (case 7F); in two others (cases 9 and 11), the ratings in Ref. E-32 were averages for the force-sensing and position-sensing runs. The reasons for the other differences are not known, and these differences make no overall difference in the data correlation.



a) Original Analysis Reproduced from Page 120 of Ref. E-32



* Provided that $\Phi(j\omega_c) = \measuredangle \frac{n_{z_p}}{F_s}(j\omega_c) - 14.3\omega_c < -180^\circ$

b) New Analysis with Added Configurations

Figure E-30. Average Handling Qualities Ratings *vs.* Pitch Attitude Phase Angle for the Neal-Smith Data Base

Figure E-30a was the basis for the Smith-Geddes pilot rating prediction (Figure E-29). As Figure E-30 shows, there is a very definite trend. The data in Figure E-30b are not quite as clean as those in Figure E-30a, however. Six cases with Level 2 ratings appear in the Level 1 region; two (8A and 14) fail the rise time requirement (t_q is too short), so Level 2 ratings are expected. Case 7P was rated a 4, or almost Level 1, on a single evaluation. Case 12 was evaluated three times, with ratings of 5, 6, and 6; and case 13 twice, with HQRs of 7 and 5.5. The reasons for the Level 2 ratings for these cases are not as clear. Because they reportedly failed the criterion for exclusion listed on Figure 3a, they were not considered in Ref. E-32. Yet both should have been included. If the feel system were removed from the dynamics of these cases, they shift only about 4 deg to the left, so it is not the inclusion of the feel system that explains the ratings.

While the occurrence of Level 2 ratings in the Level 1 region is not desirable, of more concern are those cases with ratings *better* than predicted, because this may indicate unnecessary conservatism. There are five such cases with Level 1 ratings in the Level 2 region on Figure E-30b (1B, 2F, 6B, 11, and 11(f)), and four with Level 2 ratings in the Level 3 region (1E, 2H, 2J, and 6D). This leaves 43 in the proper Level — a good total considering there were only two pilots in the Neal-Smith experiment, and several of the evaluations were by only one of the pilots. Some spread in ratings is therefore expected.

The effectiveness of the Smith-Geddes criteria in predicting the HQRs from the Neal-Smith data base is summarized in Figure E-31a. Of the 62 cases (including the six not plotted on Figure E-30b), 46 are correctly predicted by Level, for a success rate of 74%. The conservatism of the criteria is illustrated by the fact that, of the 16 that do not correlate, 13 (21% of the total) are predicted to be worse than the actual ratings indicate, while only three (5%) are predicted to be better.

PIO ratings. Evaluation of the Smith-Geddes criteria as PIO predictors requires an interpretation of the PIO rating scale (shown in Figures E-32 and E-33).

The assignment of PIO ratings has become a standard procedure in Calspan-conducted handling qualities flight research experiments. In all the NT-33A and TIFS experiments reviewed in this discussion both Cooper-Harper HQRs and PIO tendency ratings are available.

Unlike the HQR scale, the PIO tendency rating scale does not break down into "PIO/No PIO" decisions. The concern, then, is — for what PIO rating do we consider the PIO susceptibility to be real?

There are essentially two versions of the PIO tendency rating scale. The first, developed by Cornell Aeronautical Labs (now Calspan) for Ref. E-35 and used in early flight research experiments, consists of a series of adjectival phrases describing the response of the airplane (Figure E-32) . This scale was used,

a) Handling Qualities Level

Predicted Level \ Actual Level	1	2	3
3	0	4	13
2	9	28	0
1	5	3	0

Predicted Correctly: 46/62 = 74%
Predicted Better: 3/62 = 5%
Predicted Worse: 13/62 = 21%

a) Handling Qualities Level

Predicted \ Actual	No PIO	PIO
PIO	3	17
No PIO	41	1

Predicted Correctly: 58/62 = 94%
Correctly Predict PIO: 17/20 = 85%

b) PIO Tendency

Figure E-31. Summary of Effectiveness of Smith-Geddes Criteria for Neal-Smith Data Base

DESCRIPTION	NUMERICAL RATING
NO TENDENCY FOR PILOT TO INDUCE UNDESIRABLE MOTIONS	1
UNDESIRABLE MOTIONS TEND TO OCCUR WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BY PILOT TECHNIQUE.	2
UNDESIRABLE MOTIONS EASILY INDUCED WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. THESE MOTIONS CAN BE PREVENTED OR ELIMINATED BUT ONLY AT SACRIFICE TO TASK PERFORMANCE OR THROUGH CONSIDERABLE PILOT ATTENTION AND EFFORT.	3
OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST REDUCE GAIN OR ABANDON TASK TO RECOVER.	4
DIVERGENT OSCILLATIONS TEND TO DEVELOP WHEN PILOT INITIATES ABRUPT MANEUVERS OR ATTEMPTS TIGHT CONTROL. PILOT MUST OPEN LOOP BY RELEASING OR FREEZING THE STICK.	5
DISTURBANCE OR NORMAL PILOT CONTROL MAY CAUSE DIVERGENT OSCILLATION. PILOT MUST OPEN CONTROL LOOP BY RELEASING OR FREEZING THE STICK.	6

Figure E-32. Pilot Induced Oscillation Tendency Rating Scale, Circa 1966 (Ref. E-35)

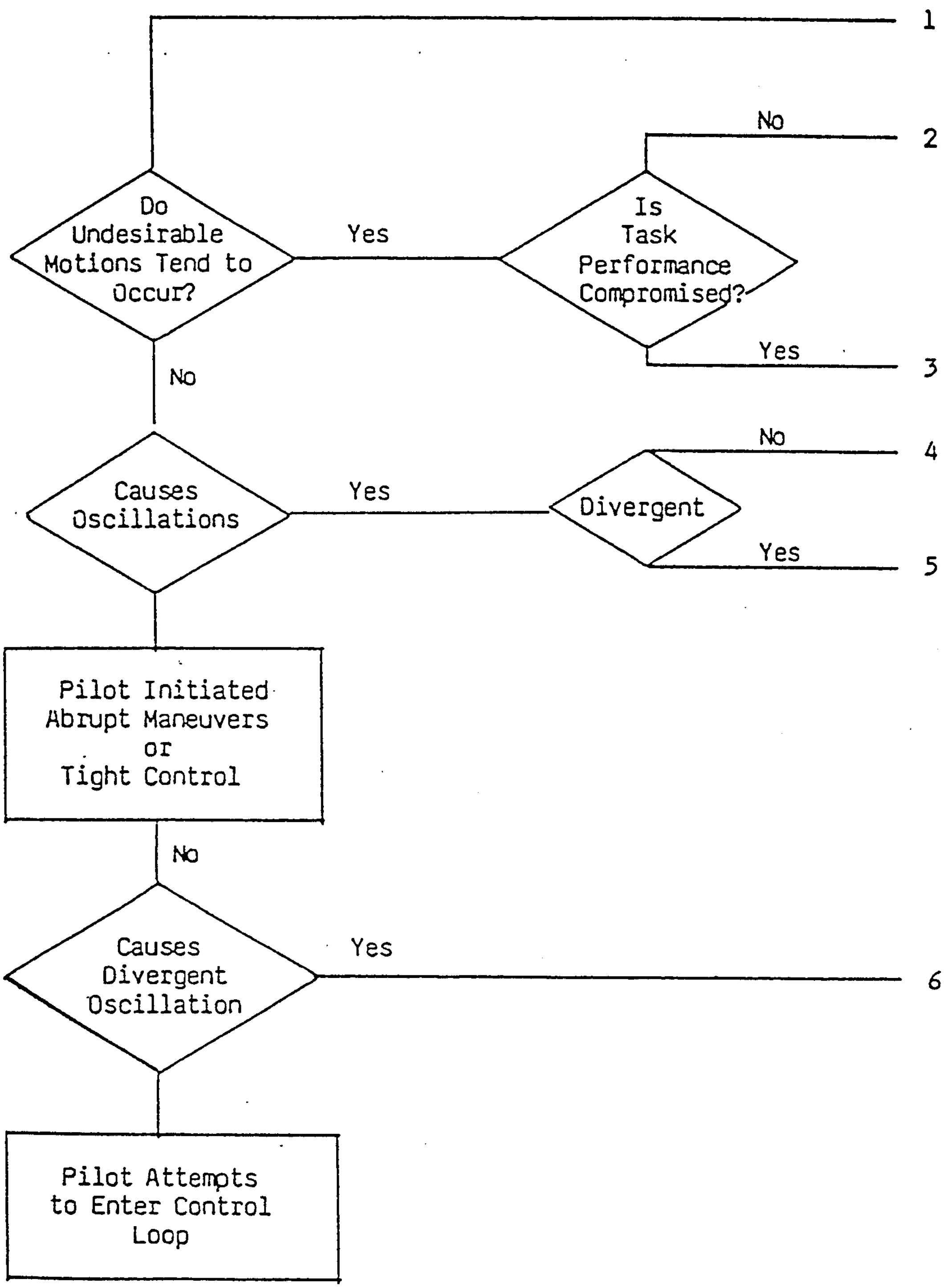


Figure E-33. PIO Tendency Classification Scale, Circa 1980 (Ref. E-36)

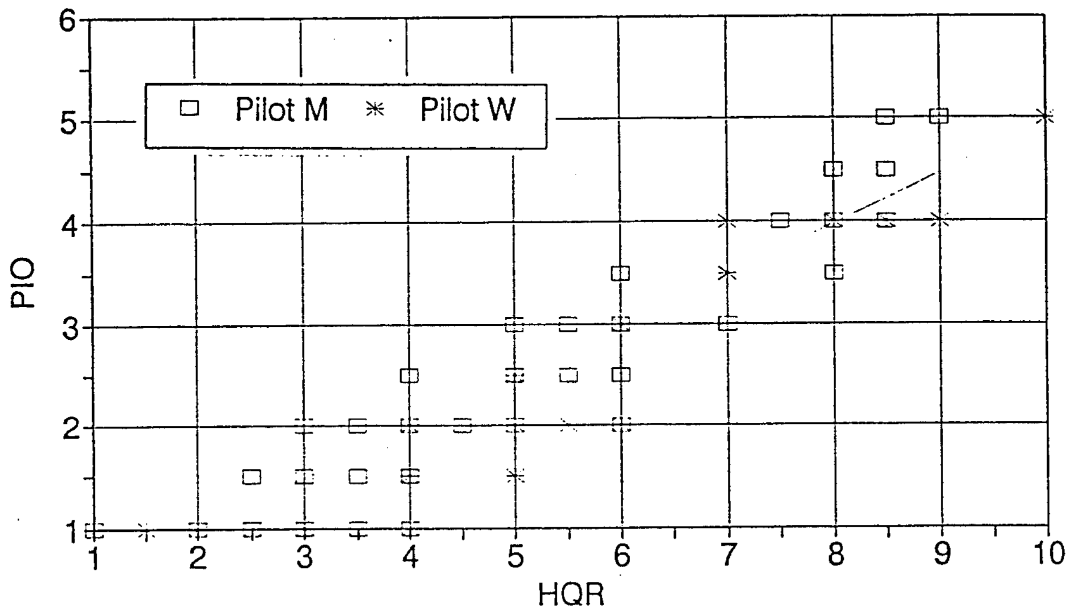
for example, in the Neal-Smith study. It is similar in construct to the older pilot rating scales, such as the Cooper and CAL scales (e.g., Ref. E-13).

In the 1980s (Ref. E-36) a decision-tree form of the PIO scale was developed by Calspan (Figure E-33) that reduces the adjectives to yes/no questions, similar in structure to the Cooper-Harper HQR scale. This scale appears alone in the Calspan references, but in some reports both scales are shown. It is not clear whether the evaluation pilots were actually instructed to apply both forms of the scale prior to assigning ratings; there are no significant differences in the two scales, but such a dichotomy of structure could lead to differences between pilots in their assignment of PIORs.

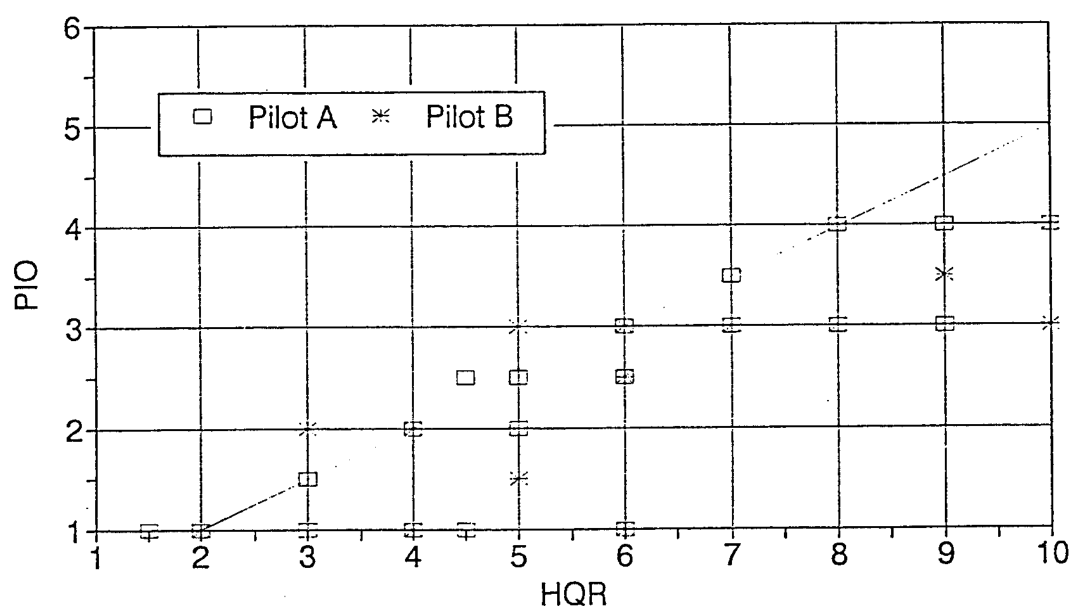
For both forms of the PIO rating scale, it is possible to obtain PIORs of 1, 2, or 3 without actually encountering a PIO or any hint of a PIO. For example, in the adjectival scale of Figure E-32 a PIOR of 3 is assigned when "Undesirable motions [are] easily induced." There is no requirement that these motions be oscillatory in nature; for this reason, it is not unexpected that occasional pitch bobble, that does not develop into a PIO, may be sometimes be given a PIOR of 3.

It has been reported in numerous references (e.g., by Neal and Smith, among others) that there is a strong interrelationship between the HQRs and PIORs assigned by evaluation pilots. This is not surprising, in the context of the PIOR scale, for ratings up to 3 or 4, since "undesirable motions" indicate poor handling qualities as well. The interrelationship between ratings is evidenced by data from both the Neal-Smith and LAHOS studies, shown in Figure E-34. For both sets of data, the ratings are almost entirely within one rating point of a relationship defined by PIOR = 0.5 HQR. There is no reason why this must always be true; for example, if a particular airplane has adequate response bandwidth, but no control power, it would be expected to be extremely sluggish and perhaps uncontrollable, but not susceptible to PIO. Such an airplane might receive HQRs of 9 or 10 and PIORs of 1. This particular example could not have occurred in either the Neal-Smith or LAHOS studies, since the pilots were allowed to select control sensitivities appropriate for the tasks. Thus, for these studies, undesirable motions and oscillations were likely if the aircraft dynamics were inadequate and the pilots attempted to compensate through control sensitivity, and hence the PIORs and HQRs would be expected to be correlated to some extent.

Explicit mention of "oscillations" occurs only for PIORs of 4 or worse in the Figure E-32 scale. Figure E-33 is even clearer, since PIORs of 1, 2, and 3 can be given only if the pilot answers "No" to the question of "causes oscillations[?]" and 4 or worse must be given if the answer is "Yes." This suggests that PIO potential is indicated by a PIOR of 4 or worse, and such a division may be entirely reasonable.



a) Neal-Smith Data



b) LAHOS Data

Figure E-34. HQR *vs*. PIO Rating

It is important to remember, however, that we are worried about a *potential* for PIOs, and not necessarily whether a fully-developed PIO just occurred. Certainly, if we want to prevent PIOs, then we should used PIORs of 4, 5, or 6 as indicators. This presupposes that the assignment of a PIOR of 2 or 3 indicates that "undesirable motions" were encountered by the pilot, but that these motions did not, and *never will*, develop into full-blown PIOs. Since PIOs are, by their nature, infrequent and unpredictable, it would seem unreasonable to assume that an aircraft with PIORs of 3 has no tendency to PIO. It is possible that, given more evaluation time, such an aircraft may exhibit a potentially catastrophic PIO.

Whether the aircraft exhibited a real PIO or not, the pilot assignment of a PIOR of 3 indicates that 1) undesirable motions did, indeed, occur, and 2) task performance was compromised as a result. While such undesirable motions should also result in a degraded HQR (since the handling qualities must be degraded as well), they are a warning that some potential may exist for these motions to become oscillatory. At the least, the fact that the motions compromise performance says that they should be regulated against.

On this basis, it has been assumed in this report that a PIOR worse than 3 indicates a potential for PIOs. For data correlation purposes, it has further been assumed that a PIOR of exactly 3.0 represents the "best-case" scenario: if it occurs in a region where PIO is predicted, a 3.0 is considered to predict PIO, and if it is in a region where no PIO is predicted, it is considered to predict no PIO.

The level of maturity for PIORs is well below that for HQRs, and many interpretations are possible. Unanswered questions include the following:

- Should we separate the scale further, into effective Levels, such as "Acceptable" (PIORs of 1 to 2.5), "Undesirable but no PIO" (PIORs of 2.5 to 4), "Controllable PIOs" (PIORs of 4 and 5), and "Uncontrollable PIOs" (PIOR of 6)?

- Is an average PIOR reasonable? For example, if three pilots evaluate a particular aircraft and assign PIORs of 1, 1, and 5, the average is 2.33, and, by the interpretation in this working paper, the potential for PIO is low. But one of the pilots reports encountering divergent oscillations! The use of the worst PIOR, rather than the average, may be more reasonable — except, as with HQRs, this places an extremely high weight on one pilot's opinion, from perhaps no more than two or three short exposures to the aircraft. It is always possible that some other feature of the aircraft was responsible for the third pilot's rating — incorrectly set control sensitivity, wrong configuration, etc. Ignoring the opinions of two out of three pilots is not appropriate for HQRs, and it is probably not appropriate for PIORs either. In any case, it is more important to determine why the third pilot gave the poor rating, and investigate further to determine if this pilot saw a real problem that the other pilots failed to see.

- Can we really determine "PIO tendencies" based on PIORs? Unlike handling qualities, PIOs are sporadic events that occur only rarely. As discussed above, PIORs of 4, 5, and 6 only tell us that PIOs occurred; better ratings do not preclude the possibility for PIOs. This is a question that may simply not be answerable — if, during the lifetime of an operational airplane, one or two PIOs are encountered, is this statistically sufficient to consider the airplane "PIO prone?" How many PIOs does it take, and what is the likelihood that, given perhaps ten evaluations by two or three test pilots, such a tendency would be exposed? It is for this reason that PIORs of 3 or worse are considered to be signs of a potential for PIOs.

Figure E-35 shows the average PIORs for the Neal-Smith data plotted against the attitude phase angle. Unlike Figure E-30, all 62 cases are included here. The cases not on Figure E-30b are labeled on Figure E-35. Figure E-31b summarizes the effectiveness of the Smith-Geddes criteria for predicting PIORs: 58 out of 62, or 94% — an excellent number, well above the handling qualities Level success rate of 74%. Of the 20 cases predicted to exhibit PIOs, 17 were correctly predicted, for a success rate of 85%.

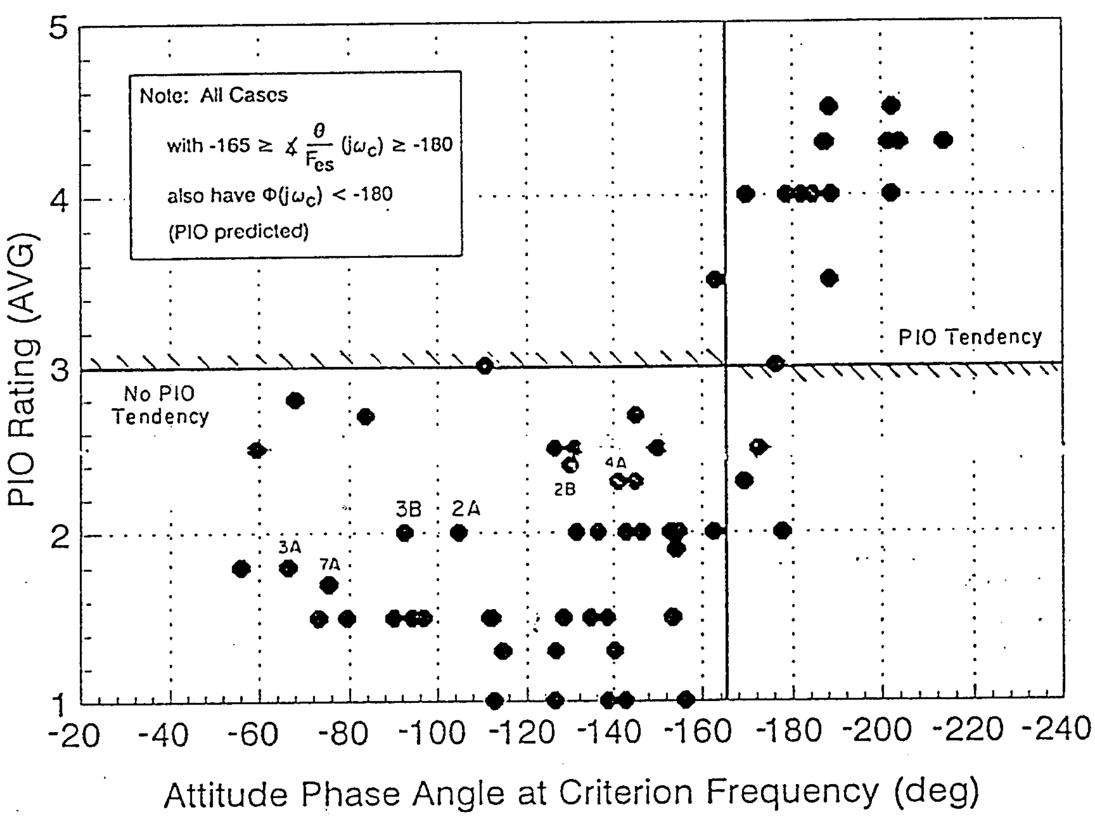


Figure E-35. Average PIO Rating *vs.* Pitch Attitude Phase Angle for the Neal-Smith Data Base

c. Data for Fighter Aircraft: Precision Landing (Category C) Pitch Control

In the extension of the Smith-Geddes criteria to precision landings, it is necessary to assume that the Smith-Geddes criteria still apply. It has been report that the criteria "apply regardless of piloting task, flight condition, or aircraft type or size" (Ref. E-29). The underlying hypothesis is that, driven to tightly track attitude, the likelihood for PIO is as great in landing as in up-and-away flight; and in addition, it is as likely that the pilot will be driven to tightly track attitude in the first place. This philosophy is counter to all other short-term pitch response criteria in MIL-STD-1797A, where landing is considered a different task and one that requires a different task bandwidth, and, therefore, a different level of dynamics.

It is not possible to conclusively resolve the fundamental differences in philosophy between the Smith-Geddes and all other criteria; it may be true that the potential for PIOs is equally great in landing as in up-and-away flight. The philosophy behind most criteria (including Bandwidth), however, is that this is not the case. In air tracking, the pilot's primary concern is attitude – keep the nose on the target (or, in the case of the Neal-Smith study, keep the pitch attitude tracking errors to a minimum). By contrast, in landing pitch attitude is used as an inner loop to control sink rate, so the likelihood for tightly entering the attitude loop during landing is much lower. High-bandwidth control is possible, but the purpose of this control is to achieve precise flightpath control, not control of a gunsight pipper. In reading all of the landing data analyses that follow, it is important to keep this fundamental difference in mind.

For fighter aircraft in precision landings, there are four primary sources of data. Three were generated with the USAF variable-stability NT-33A and the fourth with the NASA digital fly-by-wire F-8. Of the NT-33A references, one is well-known: the LAHOS experiment, Ref. E-5, conducted by Calspan. The other two are not as well publicized but are still very important: flight test programs conducted by students of the USAF Test Pilot School and documented in theses from the Air Force Institute of Technology (HAVE PIO, Ref. E-37, and HAVE CONTROL, Ref. E-38). These references provide both HQRs and PIORs, and Ref. E-37 also documents the occurrence of PIOs and the PIO frequencies.

In the LAHOS experiment a total of 49 configurations were evaluated on the NT-33A by one or both of two test pilots. The design of the experiment was similar to that of the Neal-Smith study, except position sensing commands were used, rather than force, and hence most of the analyses that follow include the dynamics of the feel system. The landing task was performed three times, including two visual landings with an intentional offset maneuver on close final. Required touchdown zone was clearly marked on the runway.

As with the Neal-Smith data, these data have been analyzed in great detail and are the source of many new and revised criteria. The Category C Bandwidth requirements discussed in this appendix were based entirely on the LAHOS data.

Handling Qualities Ratings. When the average HQRs from the LAHOS program are compared with the Smith-Geddes criteria (Figure E-36), there is an apparent trend in pilot ratings. The degradation in HQR with increasing attitude phase angle is quite similar to that for the Neal-Smith data in Figure E-30. There is, however, a significant shift in the ratings to the right when compared with the Smith-Geddes boundaries. These data suggest that the Smith-Geddes criteria are too conservative; this disparity was also noted by Smith (Ref. E-33) and by Calspan in an earlier independent review (Ref. E-39). In Ref. E-33 Smith speculates that the reason for this disparity may be task-related: pilots are not required to operate in a closed-loop fashion as tightly in landing as they are in up-and-away tracking. As a result, Smith theorizes, PIOs are not as likely to be exposed in a landing evaluation, even though the potential is high, as his criteria predict.

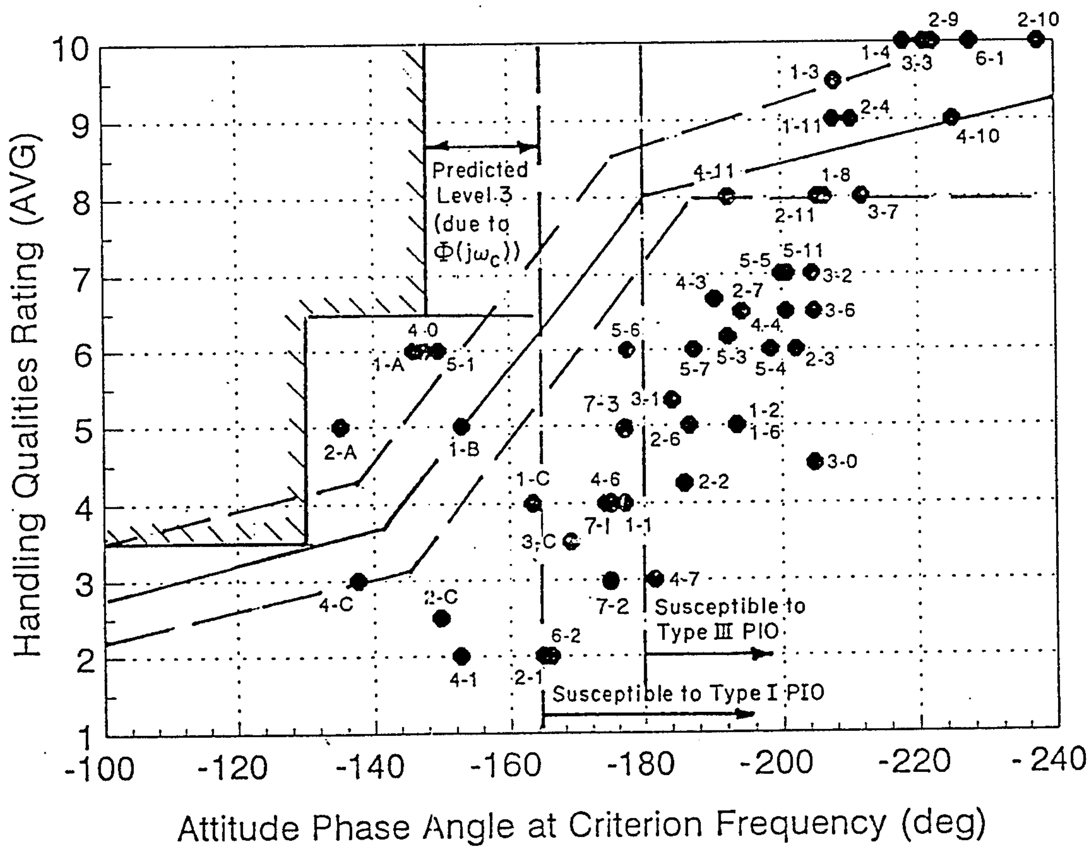


Figure E-36. Average Handling Qualities Ratings *vs.* Pitch Attitude Phase Angle for the LAHOS (Ref. E-5) Data Base

It is possible that Smith's hypothesis is correct. It may be countered, however, that the data upon which his criteria are based are subject to criticism of a similar nature: in the Neal-Smith experiment, the pilots were required to perform tight pitch tracking *only*, without regard for flightpath or normal acceleration control. In a real air-to-air combat environment, the pilot's concern is not solely on attitude control, but also on attaining and retaining a firing solution on the target by controlling flightpath relative to the target. By eliminating this aspect of longitudinal control, the experimenters in the Neal-Smith program may have driven the pilots into unreasonable and totally unrealistic closed-loop operation.

It is also possible that pilots simply do not need the same level of response for landing as for air combat. This is the basis for the division of requirements in MIL-STD-1797A by mission phases and categories. It is the basis for allowing a lower short-period frequency or lower pitch attitude Bandwidth for landing. Pilots simply do not *need* the same level of Bandwidth to land.

A counter argument has been raised that the occurrence of PIOs in landing is directly related to the triggering of some event that leads the pilot to demand high response — and since the required response isn't there, a PIO results. That is, the argument goes, there is a "primitive pilot" (Ref. E-33) that takes over in certain instances, and if the aircraft isn't capable of giving this pilot the closed-loop response he needs, the primitive pilot will get into a PIO.

It is impossible to refute this counter argument without careful testing for PIO tendencies in a flight test environment in which PIOs are encouraged. Instead, we may make the observation that, if a certain Bandwidth is good enough for landing in the constrained, precision offset landing task used in the LAHOS experiment, we do not need to demand more. The precision offset landing task is considered a valid measure of handling qualities, and therefore, we must assume, of PIO potential.

There are two primary approaches that can be taken with the Figure E-36 data: 1) ignore it out of hand, assuming there is something flawed with the task, and therefore making the Neal-Smith data the only source we can trust; or 2) accept the pilots' evaluations as valid *for this task*, and judge the effectiveness of the Smith-Geddes criteria on this basis. The latter approach is taken here.

Figure E-37a summarizes the results of the handling qualities portion of the Smith-Geddes criteria for the LAHOS data. Two sets of numbers are shown. One set is based on the attitude criterion of Figure E-36, ignoring the requirements on n_{z_p}/F_{es} (Figure E-29), while the other set of numbers includes these requirements. Because of the phase characteristics of the NT-33A in landing, the parameter $\Phi(j\omega_c)$ is more negative than -180 for several cases in the attitude region between -148 and -165 deg, and thus these cases should be Level 3 by this criterion. It may be reasonable to assume that at low speeds pilots

Predicted Level	1	2	3
3	3(5)	16(18)	20
2	4(2)	6(4)	0
1	0	0	0

Actual Level

Attitude Only:

- Predicted Correctly: 26/49 = 53%
- Predicted Better: 0/49 = 0%
- Predicted Worse: 23/49 = 47%

If n_{z_p}/F_{es} Criterion Included (numbers in parentheses):

- Predicted Correctly: 24/49 = 49%
- Predicted Better: 0/49 = 0%
- Predicted Worse: 25/49 = 51%

a) Handling Qualities Level

Predicted	No PIO	PIO
PIO	11(19)	20(21)
No PIO	18(9)	0(0)

Actual

Attitude Only:

- Predicted Correctly: 38/49 = 78%
- Correctly Predict PIO: 20/31 = 65%

If n_{z_p}/F_{es} Criterion Included (numbers in parentheses):

- Predicted Correctly: 30/49 = 61%
- Correctly Predict PIO: 21/40 = 53%

b) PIO Tendency

Figure E-37. Summary of Effectiveness of Smith-Geddes Criteria for the LAHOS Data Base

are not as sensitive to normal acceleration since a large pitch rate is required to generate any significant acceleration component.

Based on attitude only, the Smith-Geddes criteria do not predict handling qualities Levels well at all: 26 out of 49 cases, or only 53%. More significantly, the conservatism of the criteria is obvious, since the other 23 cases are all predicted to be worse than they actually were. Addition of the normal acceleration requirement only makes the criteria worse. It is possible to achieve Level 1 handling qualities with aircraft that lie in the Level 3 region on the Smith-Geddes criteria. Significantly, none of the configurations flown in the LAHOS program is predicted to be Level 1, yet seven received average HQRs of 3 or better.

A joint Air Force Institute of Technology/Test Pilot School program was conducted in 1986, specifically investigating longitudinal pilot induced oscillations on landing (Ref. E-37). The HAVE PIO program used the USAF variable-stability NT-33A with three TPS students serving as evaluation pilots. Precision offset landings were performed, with desired and adequate performance limits defined as in the

LAHOS program described above. The 18 configurations evaluated were also similar to several of those in LAHOS.

Results of the HAVE PIO program must be viewed with some caution. First, as a TPS project, it is possible that the pilots were not sufficiently experienced in evaluating flying qualities and assigning HQRs and PIORs. Second, since the project was intended to look at PIOs, the pilots may have been more conscious of any hint of a potential PIO than might normally be expected in operational flight. Nevertheless, this is an important data source because it provides not only handling qualities and PIO information, but PIO frequencies as well.

In the analysis of Ref. E-37, it is reported that 12 of the 18 configurations exhibited PIOs on landing. As is shown in the analysis that follows, however, in three of the cases the "PIO" was actually a pitch bobble; PIORs suggest PIO tendency, but when the pilots answered a pilot comment questionnaire on "PIO tendency," the answers reflected bobble with little or no PIO tendency. The three cases, PIORs, and comments on PIO tendency, were as follows:

> Configuration 2-B: Pilot A (PIOR 3): "Yes;" Pilot B (PIOR 2): "None;" Pilot C (PIORs 2 and 1 when repeated): "Slight" and "None."
>
> Configuration 3-1: Pilot A (PIOR 3): "Light low frequency bobble in flare;" Pilot B (PIOR 2): "None" (under Major Problems: "Pitch movement characterized by small jerky motions, did not affect task performance"); Pilot C (PIOR 2): "Low."
>
> Configuration 3-6: Pilot A (PIOR 2): "Slight;" Pilot C (PIOR 2): "Low. A little bobble tendency in flare."

Based on the pilot comments, these three cases are not considered PIO cases in the following discussion.

The subject of the Ref. E-37 master's thesis was the effectiveness of the Smith-Geddes criteria and potential of the Bandwidth criteria (with MIL-STD-1797 limits) as PIO predictors. The author found a very high success rate for both criteria using both the HAVE PIO and LAHOS data. The version of the Smith-Geddes criteria, however, was not that published in Ref. E-29 and widely used today. Instead, it was an early approach (Ref. E-31) that required the application of pilot-vehicle system modeling techniques to determine PIO tendency. While this approach was successful in Ref. E-37, it is obviously much too complex to ever apply in a specification; in addition, linear pilot-vehicle modeling is still somewhat of an art despite the development of rules such as those documented in Refs. E-30 and E-40. As evidence of this, consider the pilot dynamics assumed by the author of Ref. E-37: for most of the

configurations analyzed, the assumed pilot compensation was a lead at 0.5 sec (break frequency of 2 rad/sec). Based on studies of pilot opinion as a function of lead generation (documented in Ref. E-40, among other sources, and verified in the simulation reported in Ref. E-19), the expected pilot rating degradation for this level of lead, at the assumed crossover frequencies used in Ref. E-37, should have been at least two rating points. That is, the best rating one could possibly expect with this pilot model is a 3, and more likely no better than a 4. Yet in both the HAVE PIO and LAHOS experiments numerous HQRs of 2 were assigned, with occasional ratings of 1.5, suggesting the assumed pilot model was not representative of the actual pilot compensation required. If another researcher were to perform a similar analysis, it is likely that a different pilot model form would be assumed.

The following analysis of the HAVE PIO data uses the current definition of the Smith-Geddes criteria and hence the success rate is different. As the plot in Figure E-38 shows, the HAVE PIO data show trends very similar to the LAHOS data of Figure E-36: there is a definite trend for degraded HQR as phase angle becomes more negative, but the trend is well below predicted and data scatter is large. The three bobble cases discussed above are in the predicted Level 2 region; unfortunately, four cases received Level 1 average HQRs and are in the Level 2 and 3 ranges on the plot.

As with the LAHOS experiment, the NT-33A in this experiment exhibits considerable phase rolloff in the response of normal acceleration at the pilot's station. As a result, only three cases are not predicted to be Level 3.

The effectiveness of the Smith-Geddes criteria is summarized in Figure E-39a. If the normal acceleration portion of the criteria is ignored, the correct Level is predicted for 10 of the 18 cases, or 56%. Significantly, all eight of the other cases are predicted to be worse than they were actually rated. Inclusion of the normal acceleration requirement degrades the correlation only slightly, to 50%, with the other 50% predicted to be worse than they actually were.

As with the HAVE PIO experiment, HAVE CONTROL (Ref. E-38) was a joint AFIT/TPS project that used the NT-33A for evaluation of short-period dynamics. The scenarios, task, pilots, and dynamics variations were similar to those for HAVE PIO, as discussed above. The results of this experiment are documented in both Ref. E-38 and Ref. E-41. Thirteen configurations were evaluated; one (labeled configuration 1-10) was reported to be unflyable, with divergent PIOs even on downwind, so no HQR or PIOR was assigned. In order to include this case in the analysis, an overall HQR of 10 and PIOR of 6 were assumed for this configuration. In addition, in the analyses in Refs. E-38 and 41, one configuration (1-1) is reported as having received HQRs of 2 from one pilot and 4 from another; in the pilot debriefing cards in Ref. E-38, however, the ratings are 3 and 4. The latter numbers are used here.

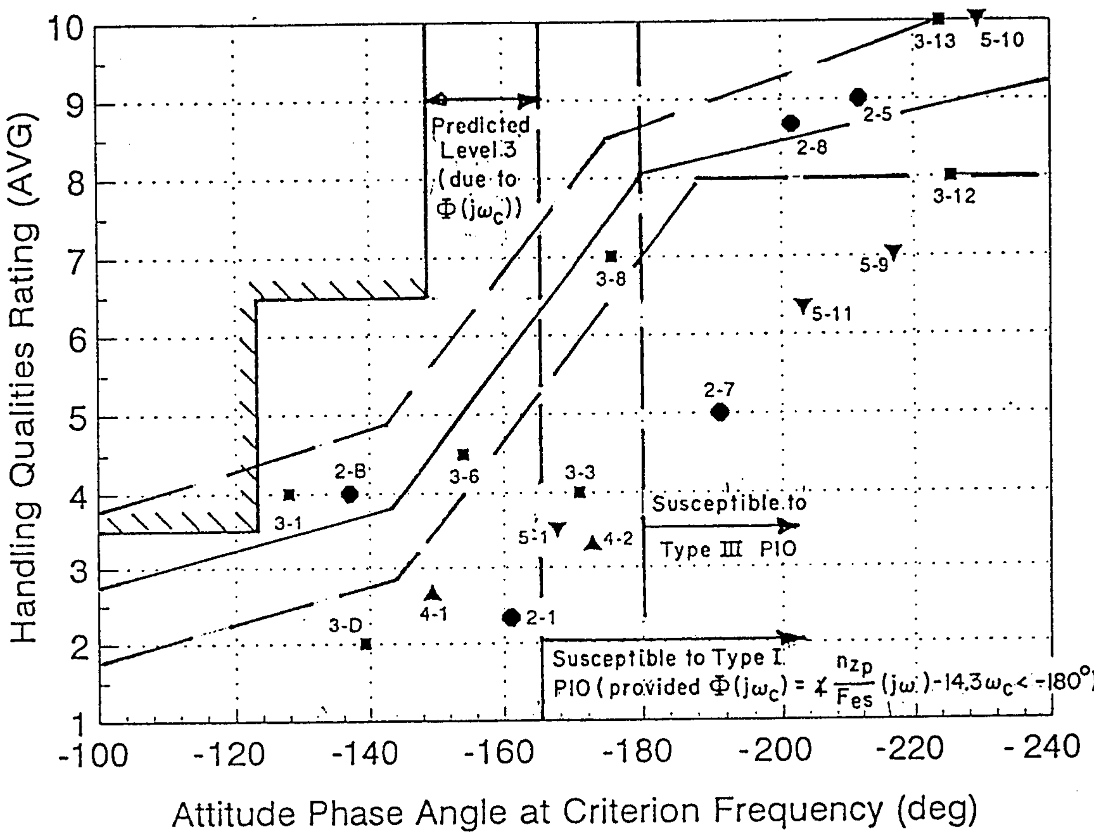


Figure E-38. Average Handling Qualities Ratings *vs.* Pitch Attitude Phase Angle for the HAVE PIO (Ref. E-37) Data Base

Predicted Level \ Actual Level	1	2	3
3	1(3)	4(5)	7
2	3(1)	3(2)	0
1	0	0	0

Attitude Only:

Predicted Correctly: 10/18 = 56%
Predicted Better: 0/18 =0%
Predicted Worse: 8/18 = 44%

If n_{zp}/F_{es} Criterion Included
(numbers in parentheses):

Predicted Correctly: 9/18 = 50%
Predicted Better: 0/18 = 0%
Predict Worse: 9/18 = 50%

a) Handling Qualities Level

Predicted \ Actual	No PIO	PIO
PIO	1(3)	8(9)
No PIO	9(6)	0(0)

Attitude Only:

Predicted Correctly: 17/18 = 94%
Correctly Predict PIO: 8/9 = 89%

If n_{zp}/F_{es} Criterion Included
(numbers in parentheses):

Predicted Correctly: 15/18 = 83%
Correctly Predict PIO: 9/12 = 75%

b) PIO Tendency

Figure E-39. Summary of Effectiveness of Smith-Geddes Criteria for the HAVE PIO Data Base

Figure E-40 shows the average HQRs for the 13 configurations plotted against attitude phase angle at the criterion frequency. These ratings, once again, show a conservatism and scatter comparable to both the LAHOS and HAVE PIO ratings. This conservatism is documented in Figure E-41a, where the criteria are effective at predicting handling qualities Level for only three of the configurations (23% success rate), and the predicted Level is one to two worse than actual for the other 10 cases. Whether the normal acceleration portion of the criteria is included makes no difference on the correlations.

PIO ratings. Almost half of the configurations in the LAHOS experiment resulted in PIOs in landing. This provides a direct measure of the efficacy of the Smith-Geddes criteria as PIO predictors. Figure E-42 shows average PIOR vs. attitude phase angle for the LAHOS, HAVE PIO, and HAVE CONTROL configurations. There is a significant scatter in the data, as PIORs of 1 and 1.5 occur to the right of the -180 deg line, and ratings vary from 1.5 to 4 at the same value of phase angle.

As for the handling-qualities comparison, it is possible to look at these data in two ways. The first is to take the Smith-Geddes criteria literally and include the normal acceleration requirement. In this case, PIORs should be 3 or less for all phase angles at or below -165 deg, and 3 or greater when phase angle is more negative than -165 deg. The second approach, using attitude alone, moves the cutoff frequency to -180 deg.

Figure E-37b included a summary of the success of the Smith-Geddes criteria for the LAHOS data (circles in Figure 16) using both approaches. Based on attitude only, the criteria are correct on 38 of the 49 cases, a 78% success rate. When normal acceleration is included, the success rate drops to 61% (30 out of 49). If we judge the criteria by their ability to correctly predict the existence of a PIO, neither approach is very good (roughly a 60% success rate). This is because there were between 11 and 19 cases that were also predicted to be bad, but were not actually rated as PIO-prone — a fairly high rejection rate.

For the HAVE PIO data, as PIO predictors the Smith-Geddes criteria work much better, as Figures E-42 (square symbols) and E-39b show. The three bobble cases have PIO ratings of around 2, but still less than 3, and thus agree with the boundaries as drawn.

If the Smith-Geddes criteria are applied as defined, three of the four cases with attitude phase angles between -165 and -180 are incorrectly predicted to be susceptible to PIO. If the normal acceleration portion is ignored, one of the four is incorrectly predicted to be not susceptible. As Figure E-39b indicates, in either case the criteria are very successful at predicting tendency for PIOs. Unfortunately, as with the LAHOS data, the HAVE PIO data show the Smith-Geddes criteria to be conservative.

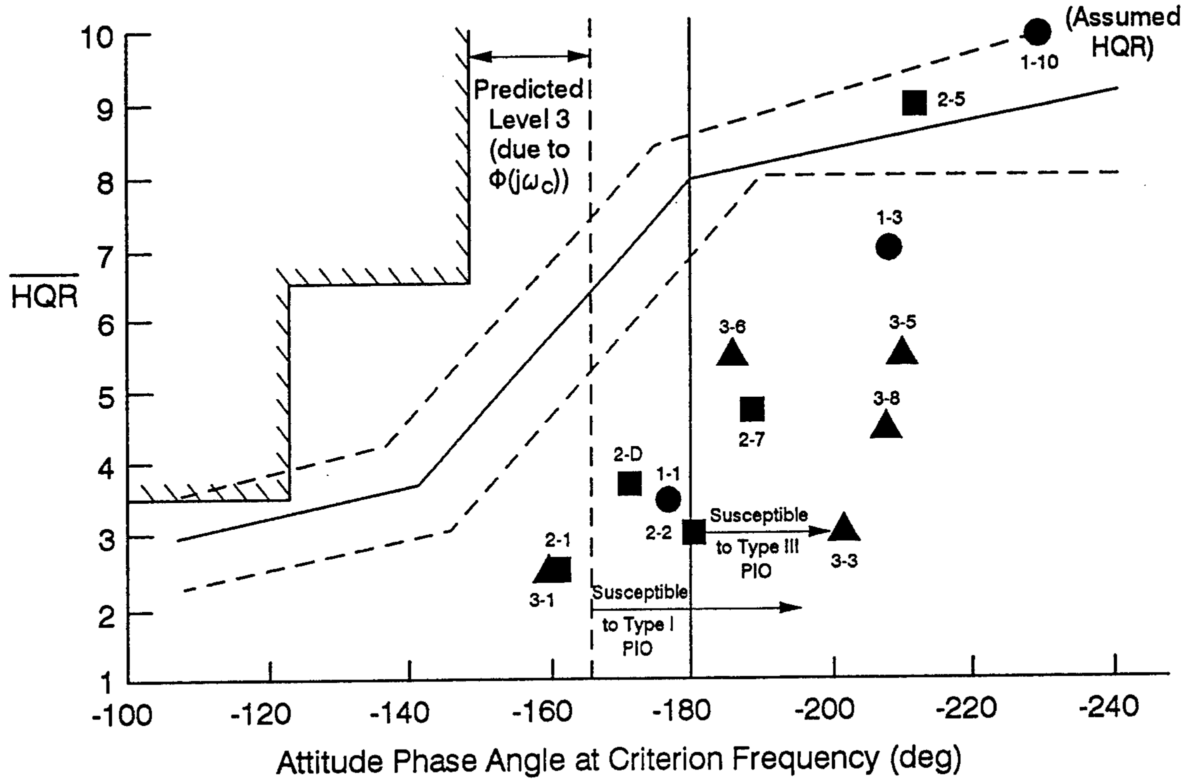


Figure E-40. Average Handling Qualities Rating *vs.* Pitch Attitude Phase Angle for the HAVE CONTROL (Ref. E-38) Data Base

Predicted Level	Actual Level 1	Actual Level 2	Actual Level 3
3	2(4)	6	3
2	2(0)	0	0
1	5	0	0

Either Method:

Predicted Correctly: 3/13 = 23%
Predicted Better: 0/13 = 0%
Predicted Worse: 10/13 = 77%

a) Handling Qualities Level

Predicted	Actual: No PIO	Actual: PIO
PIO	4(6)	5(5)
No PIO	4(2)	0(0)

Attitude Only:

Predicted Correctly: 9/13 = 69%
Correctly Predict PIO: 5/9 = 55%

If n_{zp}/F_{es} Criterion Included (numbers in parentheses):

Predicted Correctly: 7/13 = 54%
Correctly Predict PIO: 5/11 = 45%

b) PIO Tendency

Figure E-41. Summary of Effectiveness of Smith-Geddes Criteria for the HAVE CONTROL Data Base

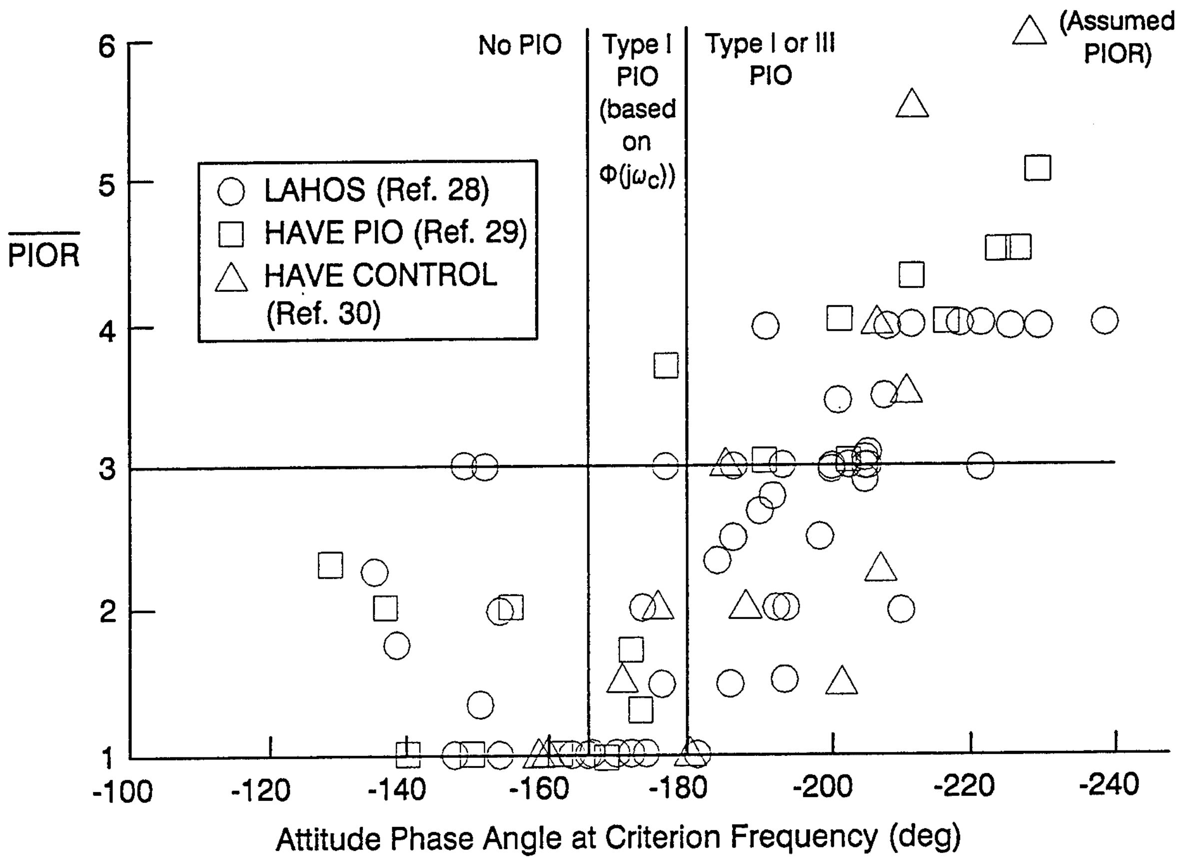


Figure E-42. Average PIO Rating *vs*. Pitch Attitude Phase Angle (NT-33A Category C Data)

For the HAVE CONTROL data in Figures E-42 (triangle symbols) and E-41b, if the criterion for PIOs is attitude only, four of the 13 cases received PIORs less than 3 but lie in the PIO region (phase angle more negative than -180 deg); if the normal acceleration requirement is added, the two cases between -165 and -180 deg are added, and six of 13 are incorrectly predicted to be PIO prone. As the summary in Figure E-41b indicates, either method picks up all of the actual PIO cases, but both include several very good cases as well.

Effect of ignoring feel system. As discussed earlier, there continues to be some disagreement on whether to consider the cockpit force feel system a part of the aircraft dynamics, or to ignore it entirely. As a test of this issue, the PIOR data for the three NT-33A landing experiments are replotted in Figure E-43 with the feel system effects removed from the attitude phase angle values. With the feel system removed, the data are all shifted to the left, but the scatter between configurations is unchanged. It is still common to find PIORs ranging from 1.5 to 4 at a similar value of phase angle.

There are several possible explanations for the trends seen in Figures E-42 and E-43. 1) The landing task is not a valid task for assessing PIO tendencies. 2) These experiments were not well-constrained to minimize pilot rating scatter. The fact that the evaluation pilots in the two TPS experiments were TPS students, as opposed to experienced test pilots, could explain some of the possible scatter. 3) The Smith-Geddes criteria are too conservative to apply to aircraft operating at landing speeds, and they do not include the important effect of high-frequency phase rolloff.

As the summary in Figure E-44a indicates, for the LAHOS data the criteria are slightly better at correctly predicting presence or absence of PIOs (90% attitude-only, compared to 78% with the feel system in, and 78% attitude-plus-n_{z_p}, compared to 61% with the feel system included). For the HAVE PIO data (Figure E-44b compared to Figure E-39b), correlation is slightly worse if attitude alone is used (89% versus 94%) but better if normal acceleration is included (94% versus 83%). Finally, for the HAVE CONTROL data (Figure E-44c versus E-41b), data correlation is improved overall, but the effectiveness in correctly predicting PIOs is still not great (either way, the criteria are correct about half the time).

Pilot Ratings for F-8 DFBW Landings. A series of tests conducted by NASA Dryden Flight Research Center provides some additional supporting data (Ref. E-42). The NASA F-8 DFBW airplane was used to investigate the effects of time delays for low-L/D (shuttle-like) approaches. The approach conditions were not the same as those for the NT-33A studies, since the approach approximated the Space Shuttle's, with a two-slope glidepath starting at 10 deg and shallowing to 1 deg for the landing. This results in a lower demand on the pilot in the flare. Landings were made from both straight-in approaches and with an intentional runway offset until short final, followed by a spot landing to a designated

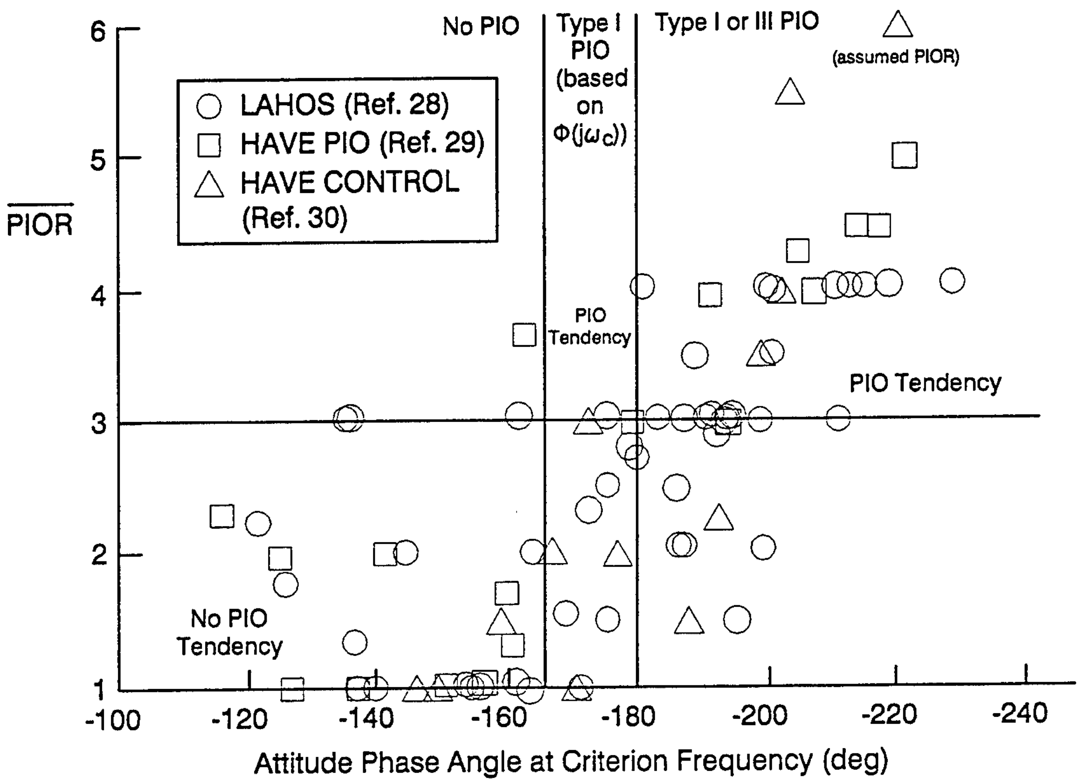


Figure E-43. Data for NT-33A Landing Experiments Replotted with Force Feel System Dynamics Removed

		Actual: No PIO	Actual: PIO
Predicted	PIO	5(11)	20(21)
	No PIO	24(14)	0(0)

Attitude Only:

Predicted Correctly: 44/49 = 90%
Correctly Predict PIO: 20/25 = 80%

If n_{z_p}/F_{es} Criterion Included (numbers in parentheses):

Predicted Correctly: 38/49 = 78%
Correctly Predict PIO: 21/32 = 66%

a) LAHOS (Ref. E-5)

		Actual: No PIO	Actual: PIO
Predicted	PIO	0(0)	7(8)
	No PIO	9(9)	2(1)

Attitude Only:

Predicted Correctly: 16/18 = 89%
Correctly Predict PIO: 7/9 = 78%

If n_{z_p}/F_{es} Criterion Included (numbers in parentheses):

Predicted Correctly: 17/18 = 94%
Correctly Predict PIO: 8/9 = 89%

b) HAVE PIO (Ref. E-37)

		Actual: No PIO	Actual: PIO
Predicted	PIO	2(5)	4(5)
	No PIO	7(3)	0(0)

Attitude Only:

Predicted Correctly: 11/13 = 85%
Correctly Predict PIO: 4/6 = 67%

If n_{z_p}/F_{es} Criterion Included (numbers in parentheses):

Predicted Correctly: 8/13 = 62%
Correctly Predict PIO: 5/10 = 50%

c) HAVE CONTROL (Ref. E-38)

Figure E-44. Summary of Effectiveness of Smith-Geddes Criteria for NT-33A Landing Data with Feel System Dynamics Removed

touchdown zone. The ratings for both types of approach will be shown, though only the offset-approach ratings are of interest here.

Average pilot ratings are shown in Figure E-45a for three conditions: straight-in (nominal) and offset approaches for a SAS mechanization, and offset approaches for a CAS control system. The ratings show a now-familiar trend of correlation with the attitude phase angle parameter, but no correlation at all with the pilot rating or Level predictions of the Smith-Geddes criteria. These data overlay those of LAHOS, HAVE PIO, and HAVE CONTROL.

Using only the eight offset-landing ratings (four for SAS and four for CAS), the Smith-Geddes criteria are not very effective in predicting Levels (Figure E-45b). All eight are well into the Level 3 region in Figure E-45a but only two received Level 3 average ratings. Again, these criteria are extremely conservative, though the lower task demands of the low L/D landings are certainly a factor as well.

Since all cases have phase angles much more negative than -165 deg (Figure E-45a), there is no difference in correlation between attitude-only and attitude-plus-acceleration criteria, or with the feel system removed. Because only HQRs were given, no analysis of PIO predictions can be made from these data.

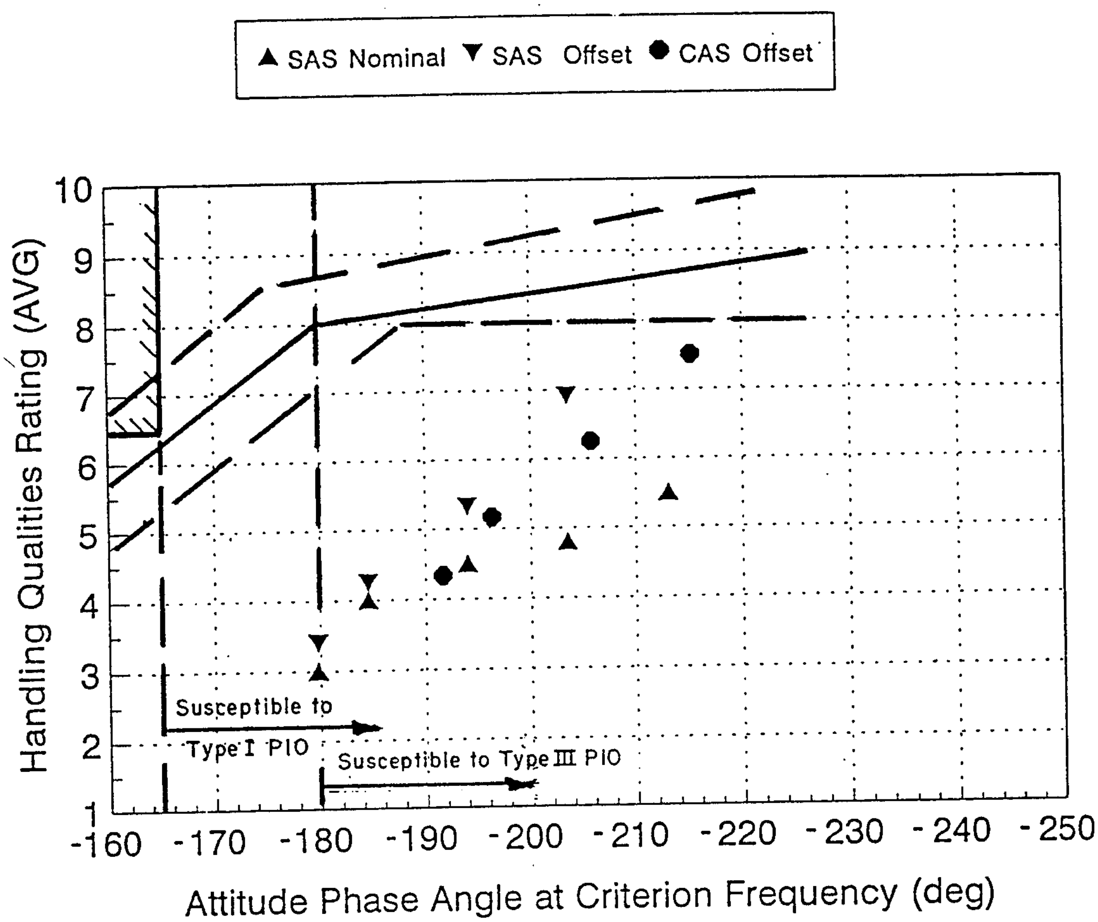
d. Data for Transport Aircraft: Precision Landing (Category C) Pitch Control

Two flight programs were conducted by Calspan using the USAF variable-stability Total In-Flight Simulator (TIFS) aircraft (Refs. E-6 and E-7). These experiments generated a total of 51 configurations (not including variations in control sensitivity) to be compared with the Smith-Geddes criteria. Both programs varied the pitch and flightpath characteristics independently, so criteria have been developed from these data for both pitch attitude and flightpath responses. Handling Qualities and PIO Ratings were obtained in the programs.

The task consisted of an offset approach with correction onto centerline at short final, followed by a flared landing. Target touchdown areas for desired and adequate performance were defined on the runway.

Because of the similarities of the two experiments, they will be considered together here. Data plots and discussions will differentiate between them when appropriate.

Handling Qualities Ratings. The data are compared with the Smith-Geddes criteria in Figure E-46. Triangles denote cases from the 1984 experiment (Ref. E-6) and circles from the 1986 experiment (Ref. E-7); solid symbols are those cases that meet the Smith-Geddes rise time requirement for Level 1.



a) Data

Predicted Level				
	3	1	5	2
	2	0	0	0
	1	0	0	0
		1	2	3
		Actual Level		

Predicted Correctly: 2/8 = 25%
Predicted Better: 0/8 = 0%
Predicted Worse: 6/8 = 75%

b) Summary of Effectiveness

Figure E-45. Average Handling Qualities Ratings *vs.* Pitch Attitude Phase Angle for NASA F-8 DFBW (Ref. E-42) Data Base

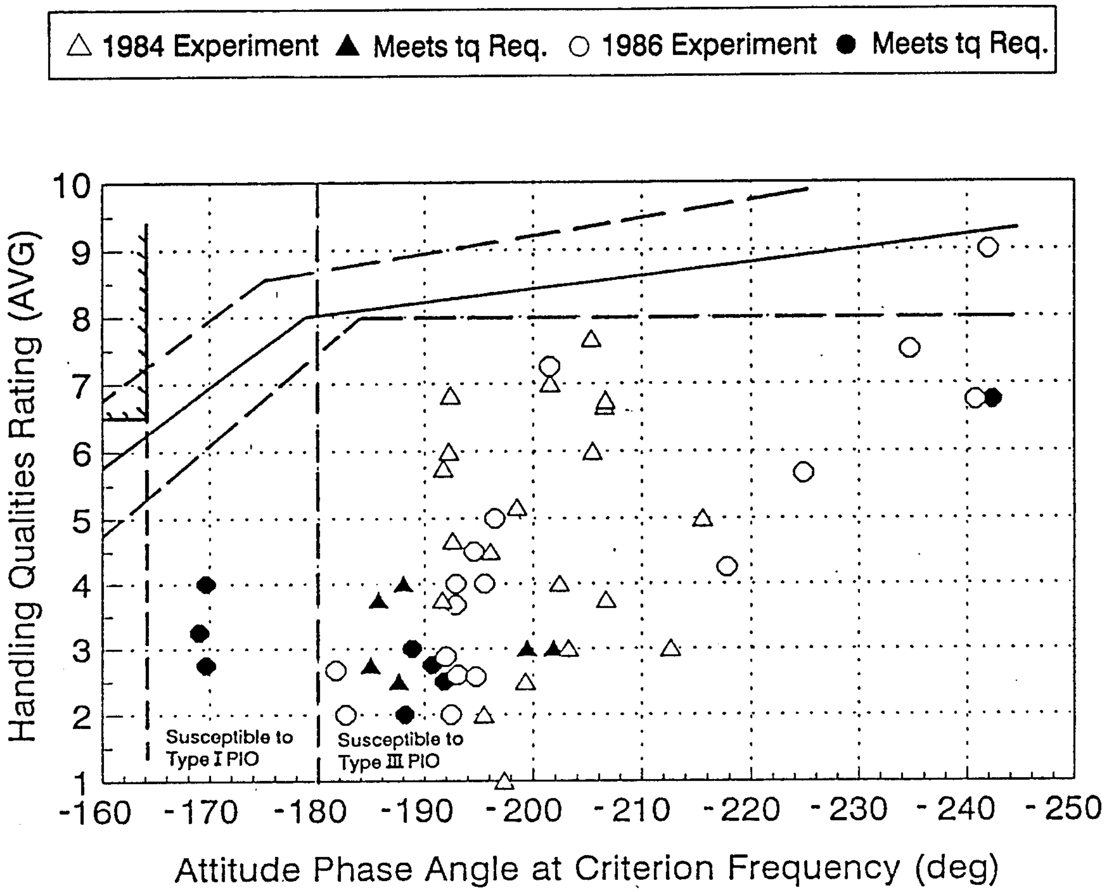


Figure E-46. Comparison of Average Handling Qualities Ratings from Two Flight Experiments (TIFS Preforming Offset Precision Landings, Refs. E-6 and E-7) with Smith-Geddes Criteria

There is a definite trend for degraded HQRs as phase angle becomes more negative. As with the fighter data reviewed above, the trend is shifted far to the right of the predicted HQR line, and the scatter in ratings is large. At a phase angle of around -192 deg, HQRs vary from 2 to 6.8 with the predominance of ratings in the range of 2 to 5.

The predictability of the Smith-Geddes criteria is very poor, as Figure E-46 shows and Figure E-47a verifies: the Smith-Geddes criteria predict all 51 of the cases to be Level 3, but only 10 of the 51 cases are in the proper handling qualities Level. The Smith-Geddes criteria, when applied to this data base, would eliminate every single case as being unacceptable, even though HQRs of 2 and 3 were common.

Predicted Level	Actual Level 1	Actual Level 2	Actual Level 3
3	21	20	10
2	0	0	0
1	0	0	0

Predicted Correctly: 10/51 = 20%
Predicted Better: 0/51 = 0%
Predicted Worse: 41/51 = 80%

a) Handling Qualities Level

Predicted	Actual: No PIO	Actual: PIO
PIO	34	14
No PIO	3	0

Predicted Correctly: 17/51 = 33%
Correctly Predict PIO: 14/48 = 29%

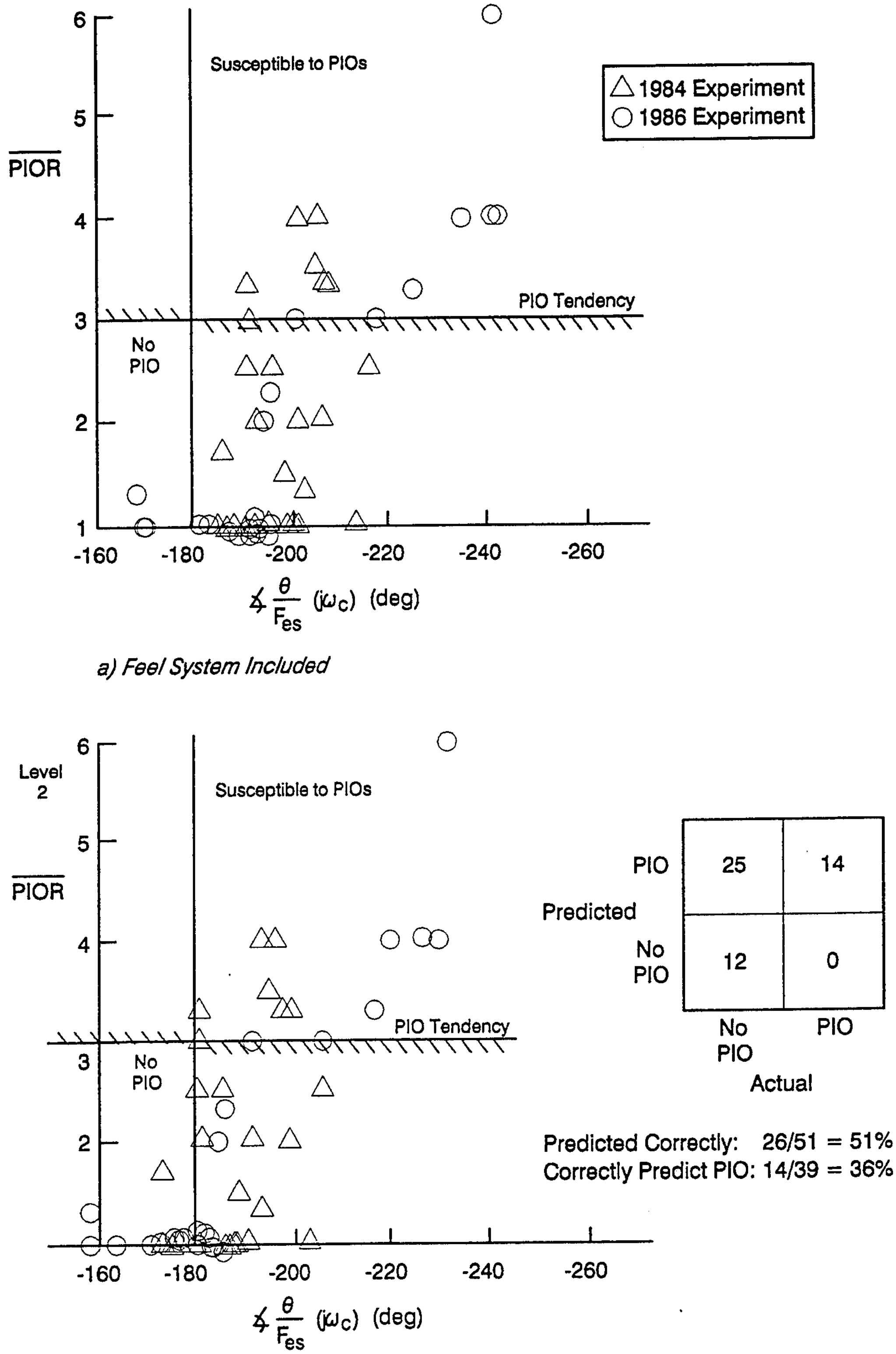
b) PIO Tendency

Figure E-47. Summary of Effectiveness of the Smith-Geddes Criteria for the TIFS Data Base

PIO Ratings. For the TIFS airplane, the normal-acceleration characteristics are such that the only PIO susceptibility criterion is that based solely on pitch attitude. Hence the -180-deg line is the relevant PIO line. The PIO ratings reflect the same trends as the HQRs (Figure E-48a). While every case with an average PIOR of 3 or greater is to the right of the -180-deg line, so are a multitude of cases that received PIORs of 1. Only three cases are to the left of the line.

It is possible that, as some argue, most of the TIFS cases were actually PIO-prone and the task simply did not expose the tendency to PIO. This cannot be verified without flying each of the cases through a more demanding task to look for PIO tendencies (which is irrelevant, since the task is *landing*), or flown for many hundreds of landings to see if a PIO ever occurs. Yet there has been no solid evidence that this is not also true for the single data set, and single task, used to generate the Smith-Geddes criteria in the first place — the Neal-Smith data. It is equally possible that the task in the Neal-Smith experiment was *too* demanding, so that otherwise perfectly good dynamics exhibited PIO tendencies. Alternatively — as hypothesized here — it is likely that the offset landing task is valid for investigating dynamics for landing, and the PIO tendencies observed are representative of those found in high-pilot-workload landings.

Taking the Smith-Geddes boundaries of Figure E-48a literally, the correlation is extremely poor, as tabulated in Figure E-47b: only 14 of the 51 cases have average PIO Ratings of 3 or more but 48 are predicted to be susceptible to PIOs. The criteria correctly predicted PIOs about one-third of the time (14/48 = 29%), meaning they were wrong more than two-thirds of the time. This says that meeting the Smith-Geddes criteria should prevent PIO tendencies — but failing them does not mean PIOs will occur.



a) Feel System Included

b) Feel System Excluded

Figure E-48. Average PIO Rating *vs.* Pitch Attitude Phase Angle for TIFS Data Base

As was found with the fighter data, there is a slight improvement in prediction if the feel system is removed. Figure E-48b shows the data plot and summarizes the effectiveness of this approach: now about half the cases (26 out of 51) are correctly predicted. Still, more are incorrectly predicted to have PIO tendencies (25) than are correctly predicted (14).

3. Development of Bandwidth and Dropback Requirements for PIO Prevention

a. <u>Data for Fighter Aircraft: Up-and-Away (Category A) Pitch Tracking</u>

The Neal-Smith data were analyzed in detail earlier in this appendix.

Pilot Ratings. Evaluation of the three Bandwidth-based criteria handling qualities criteria involves a comparison of each of the Neal-Smith configurations with the limits on pitch attitude Bandwidth and phase delay (4.2.1.2), pitch rate overshoot and pitch attitude dropback (also 4.2.1.2), and flight path Bandwidth and pitch attitude Bandwidth (4.3.1.1). The results of such a comparison are summarized in Figure E-49a. The combined criteria correctly predict the flying qualities Levels for 56 of the 62 cases, for a success rate of 90%. (Compare this to 74% for the Smith-Geddes criteria in Figure E-31a.) Two cases were predicted to be better than they actually were, and the other four were predicted to be worse.

Predicted Level	Actual Level 1	Actual Level 2	Actual Level 3
3	0	2	15
2	2	33	0
1	9	1	0

Predicted Correctly: 57/62 = 92%
Predicted Better: 1/62 = 2%
Predicted Worse: 4/62 = 6%

a) Handling Qualities Level

Predicted	Actual No PIO	Actual PIO
PIO	2	16
No PIO	43	1

Predicted Correctly: 59/62 = 95%
Correctly Predict PIO: 16/18 = 89%

b) PIO Tendency

Figure E-49. Summary of Effectiveness of the Bandwidth/Dropback Criteria for the Neal-Smith (Ref. E-4) Data

Figure E-50 shows all of the Neal-Smith cases on a crossplot of pitch attitude Bandwidth and phase delay. Pilot ratings on this figure are the PIO Ratings. Solid symbols indicate cases with excessive dropback. Several observations can be made from this figure:

- All configurations in the Level 3 region received PIORs of 3 or worse, verifying that Level 3 aircraft with high phase delay are susceptible to PIOs.

- Low-Bandwidth cases with high dropback also were considered PIO-prone. These cases actually have quite high short-period frequencies but with either low short-period damping or added dynamics that produce high overshoot ratio and gain margin limiting. Two of these cases (flagged solid points on Fig. E-50, configurations 13 and 14) were in the predicted Level 1 region on the Smith-Geddes criteria. The combination of high dropback and low Bandwidth creates dynamics that are considered only Level 2, not Level 3, but still susceptible to PIOs. (Note that neither of the two cases is ultimately counted as PIO-prone, because the average PIORs are less than 3. Yet both received PIORs of 3 from one pilot.)

- In the Level 1 and 2 regions high dropback is likely to be associated with poorer PIORs, but the average PIOR is still generally less than 2 to 2.5. Pilot comments for these configurations typically center on "pitch bobble," suggesting that high dropback contributes to greater oscillatory tendencies, but <u>not</u> to a tendency to develop a sustained, potentially explosive PIO.

Based on these observations, some tentative PIO requirements can be defined for the combination of Bandwidth and dropback:

- The aircraft will be susceptible to PIOs (i.e., PIOR $\geq$ 3) if $\tau_{p_\theta} \geq 0.19$ sec.

- There is also a possibility for PIOs if dropback is excessive and $\omega_{BW_\theta} \leq 1$ rad/sec.

- When $\omega_{BW_\theta} > 1$ rad/sec and $\tau_{p_\theta} < 0.19$ sec, excessive dropback will result in complaints of pitch bobble and degraded PIO ratings, but no tendency for sustained, potentially explosive PIOs.

Using these very simple definitions, the Bandwidth and dropback criteria are extremely accurate at predicting PIO tendencies (figure E-49b): 59 out of 62 cases, or 95%! Only configurations 4A, 5A, and 14 fail. Configuration 4A received PIORs of 2.5 and 2 with low Bandwidth and high Dropback. The average PIOR should be 3 or greater by the requirements stated above. Configuration 5A is similar, with PIORs of 3 and 1.5 from Pilot M and 3 from Pilot W. The PIOR of 1.5 is sufficient to bring the average to 2.5, but this case has low Bandwidth and high Dropback. Based on a median PIOR of 3, this case is also correctly correlated. Configuration 14 is very similar: the same pilot flew it twice, with PIORs of 2 and 3. The average PIOR of 2.5 is still marginally in agreement.

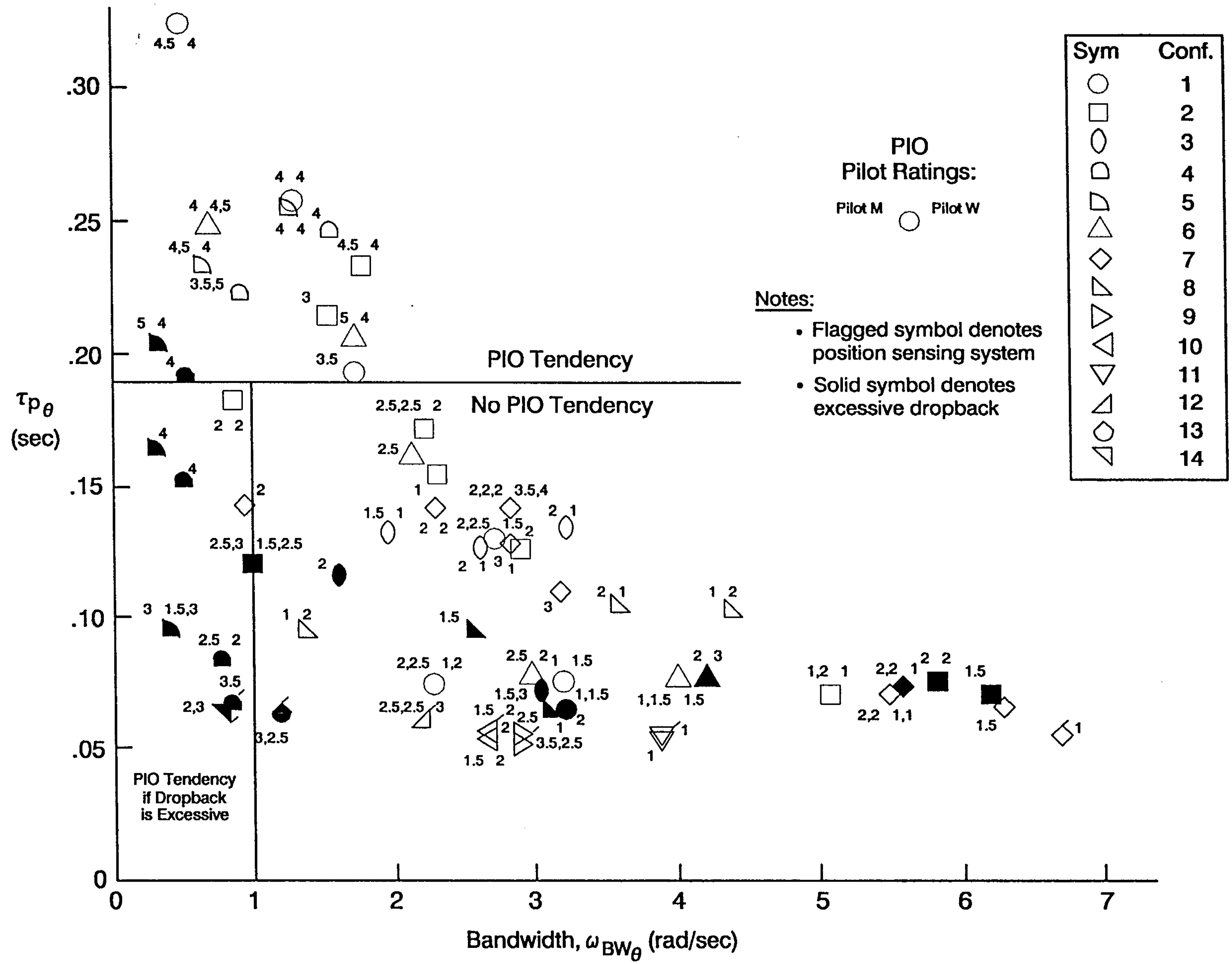


Figure E-50. PIO Ratings for Neal-Smith (Ref. E-4) Configurations on Pitch Attitude Bandwidth Boundaries

As predictors of PIO tendencies, the requirements stated above are slightly more effective than the Smith-Geddes criteria (compare figures E-31b and E-49b), with a success rate at predicting PIOs of 89% compared to 85%.

The importance of phase delay on PIO tendency is dramatically illustrated by figure E-51, where the average PIORs are plotted against pitch attitude phase delay. When $\tau_{p\theta}$ is greater than 0.19 sec, average PIOR increases from around 2, to 4 or greater.

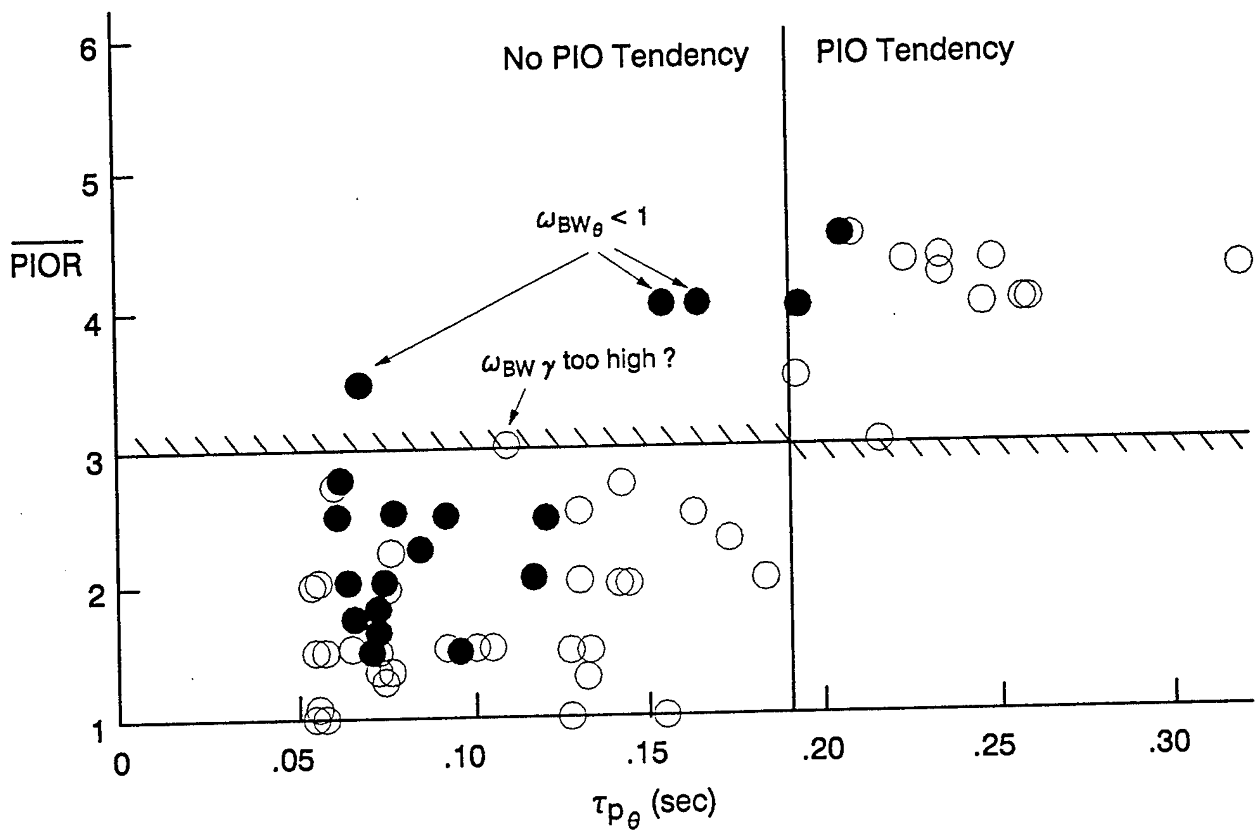


Figure E-51. Average PIO Rating *vs*. Pitch Attitude Phase Delay for the Neal-Smith Data (Solid Symbols Denote Excessive Dropback)

b. <u>Data for Fighter Aircraft: Precision Landing (Category C) Pitch Control</u>

The data from the three NT-33A experiments (LAHOS, HAVE PIO, and HAVE CONTROL) were analyzed in detail earlier in this appendix.

Pilot Ratings. Figure E-52a summarizes the effectiveness of the combined criteria on pitch attitude and flight path Bandwidths and dropback in predicting handling qualities Levels for the LAHOS data. The criteria are effective for 86% of the cases. Similar summaries are given in figures E-53 and E-54 for the HAVE PIO and HAVE CONTROL data.

PIO Ratings. Figure E-55 shows the LAHOS data on a plot of pitch attitude Bandwidth versus phase delay. PIO Ratings are noted beside each symbol. Solid symbols have excessive dropback. Based on the ratings in this figure, a set of PIO tendency requirements can be defined in parallel with those for Category A:

- PIO is always possible (i.e., average PIOR of 3 or worse) if phase delay $\tau_{p\theta} > 0.15$ sec (compared to 0.19 sec for Category A, figure E-50, possibly reflecting a greater feeling of urgency in the landing task);

- There is a susceptibility to PIO if dropback is excessive and pitch attitude Bandwidth ω_{BW_θ} < 1 rad/sec.

Predicted Level	Actual Level 1	Actual Level 2	Actual Level 3
3	0	3	15
2	2	16	2
1	11	1	0

Predicted Correctly: 42/49 = 86%
Predicted Better: 2/49 = 4%
Predicted Worse: 5/49 = 10%

a) Handling Qualities Level

Predicted	Actual No PIO	Actual PIO
PIO	1	22
No PIO	26	0

Predicted Correctly: 48/49 = 98%
Correctly Predict PIO: 22/23 = 96%

b) PIO Tendency

Figure E-52. Summary of Effectiveness of Bandwidth/Dropback Criteria for LAHOS (Ref. E-5) Data

Predicted Level			
3	0	1	7
2	0	5	0
1	5	0	0
	1	2	3
	Actual Level		

Predicted Correctly: 17/18 = 94%
Predicted Better: 0/18 = 0%
Predicted Worse: 1/18 = 6%

a) Handling Qualities Level

Predicted		
PIO	0	9
No PIO	9	0
	No PIO	PIO
	Actual	

Predicted Correctly: 18/18 = 100%
Correctly Predict PIO: 9/9 = 100%

b) PIO Tendency

Figure E-53. Summary of Effectiveness of Bandwidth/Dropback Criteria for HAVE PIO (Ref. E-37) Data

Predicted Level			
3	1	2	3
2	2	3	0
1	1	1	0
	1	2	3
	Actual Level		

Predicted Correctly: 7/13 = 54%
Predicted Better: 1/13 = 8%
Predicted Worse: 5/13 = 38%

a) Bandwidth/Dropback Criteria -- Handling Qualities Level

Predicted		
PIO	2	4
No PIO	6	1
	No PIO	PIO
	Actual	

Predicted Correctly: 10/13 = 77%
Correctly Predict PIO: 4/6 = 67%

b) Bandwidth/Dropback Criteria -- PIO Tendency

Figure E-54. Summary of Effectiveness of Bandwidth/Dropback Criteria for HAVE CONTROL (Ref. E-38) Data Base

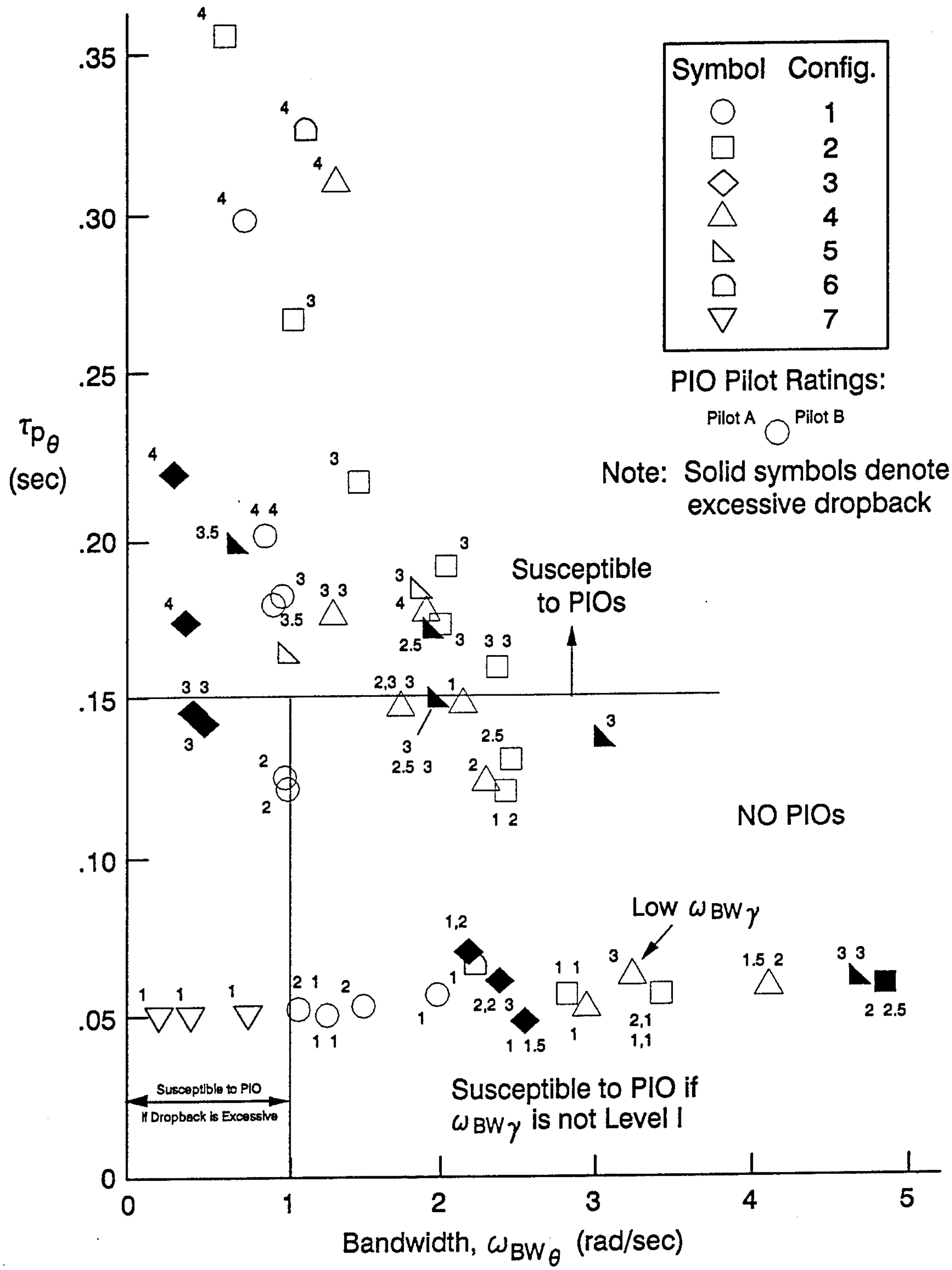


Figure E-55. LAHOS PIO Ratings on Bandwidth PIO Boundaries

- The single case with low flight path Bandwidth and a PIOR of 3 suggests that there may be a PIO tendency if pitch attitude Bandwidth is Level 1 but flight path Bandwidth is not. (This is corroborated by the transport data discussed below.)
- High dropback will result in degraded PIORs and comments of pitch bobble, with no real propensity for sustained oscillations.

These definitions are extremely successful for the LAHOS data, as the summary in Figure E-52b indicates: 48 of the 49 cases (98%) are correctly judged, with PIOs predicted for 22 of the 23 cases that actually had PIORs of 3 or greater. The only case not picked up by the requirements above is a high-dropback, high-phase-delay case that was flown once and assigned a PIOR of 2.5.

The PIORs from the HAVE PIO program are shown in Figure E-56. The nine PIO-prone cases are all caught by the $\tau_{p\theta}$ limit at 0.15 sec. The three high-dropback cases below 0.15 sec received PIORs greater than 1, but the average is still less than 3 and the comments support the observation that these cases exhibited an annoying pitch bobble, not a dangerous PIO tendency. The tentative PIO boundaries have a 100% success rate (Figure E-53b).

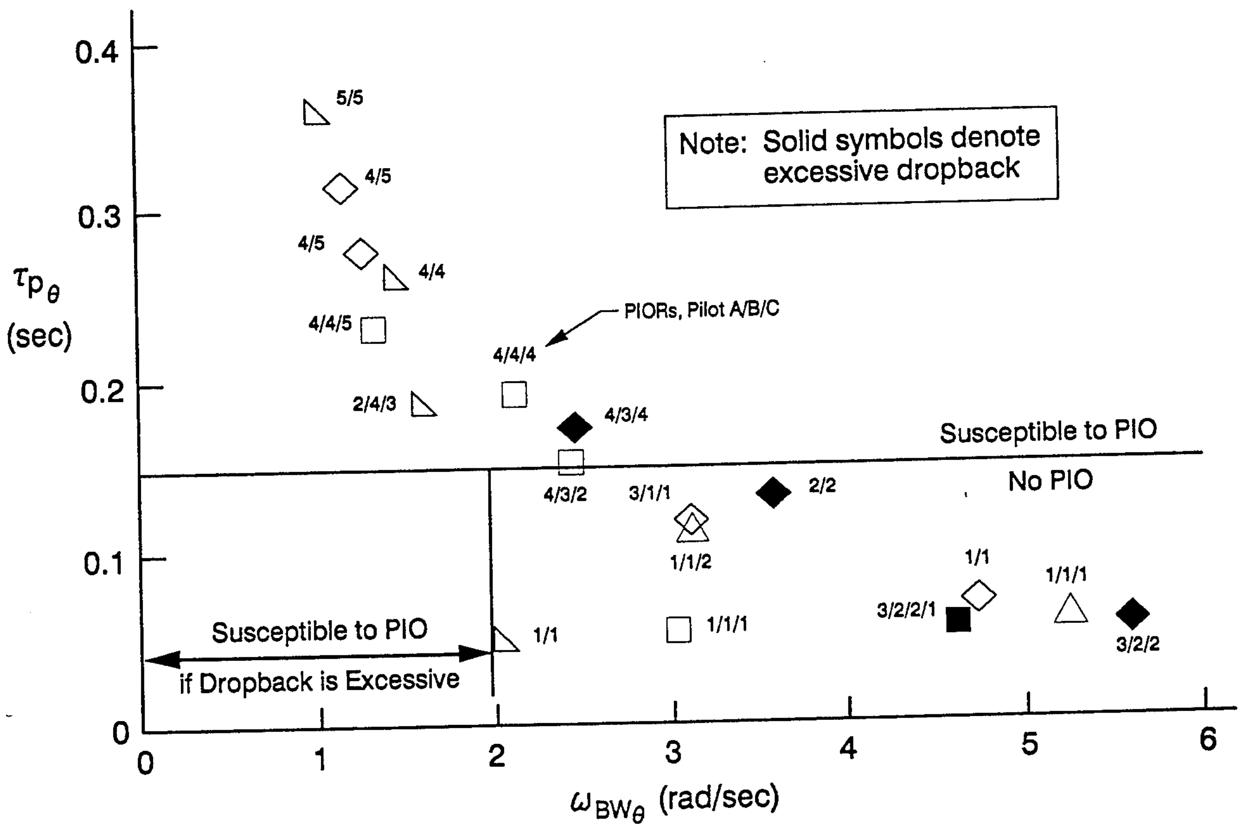


Figure E-56. PIO Ratings from HAVE PIO on Bandwidth PIO Boundaries

Figure E-57 shows the Bandwidth characteristics and PIORs of the 13 HAVE CONTROL configurations. Agreement is generally good, but certainly not as good as for the LAHOS or HAVE PIO data. Ten of the 13 cases are predicted correctly. One case with PIORs of 3 and 4 is not predicted to be PIO-prone, but the combination of excessive dropback and high phase delay may have led to the poor PIO ratings.

As with the Neal-Smith data, there is a very strong correlation between PIOR and phase delay for all of the NT-33A data, as Figure E-58 shows. In fact, this is qualitatively a much more consistent trend than that found for the Smith-Geddes criteria, either with or without the feel system. Of the 80 data points on Figure E-58, only four are not in the proper region.

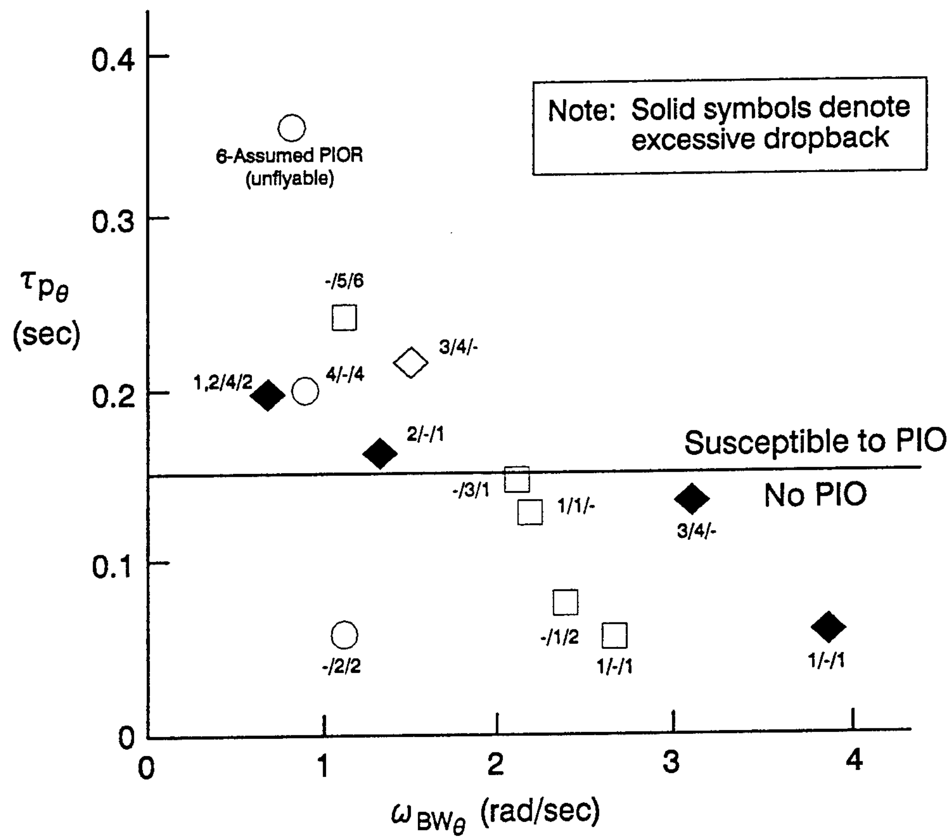


Figure E-57. PIO Ratings from HAVE CONTROL on Bandwidth PIO Boundaries

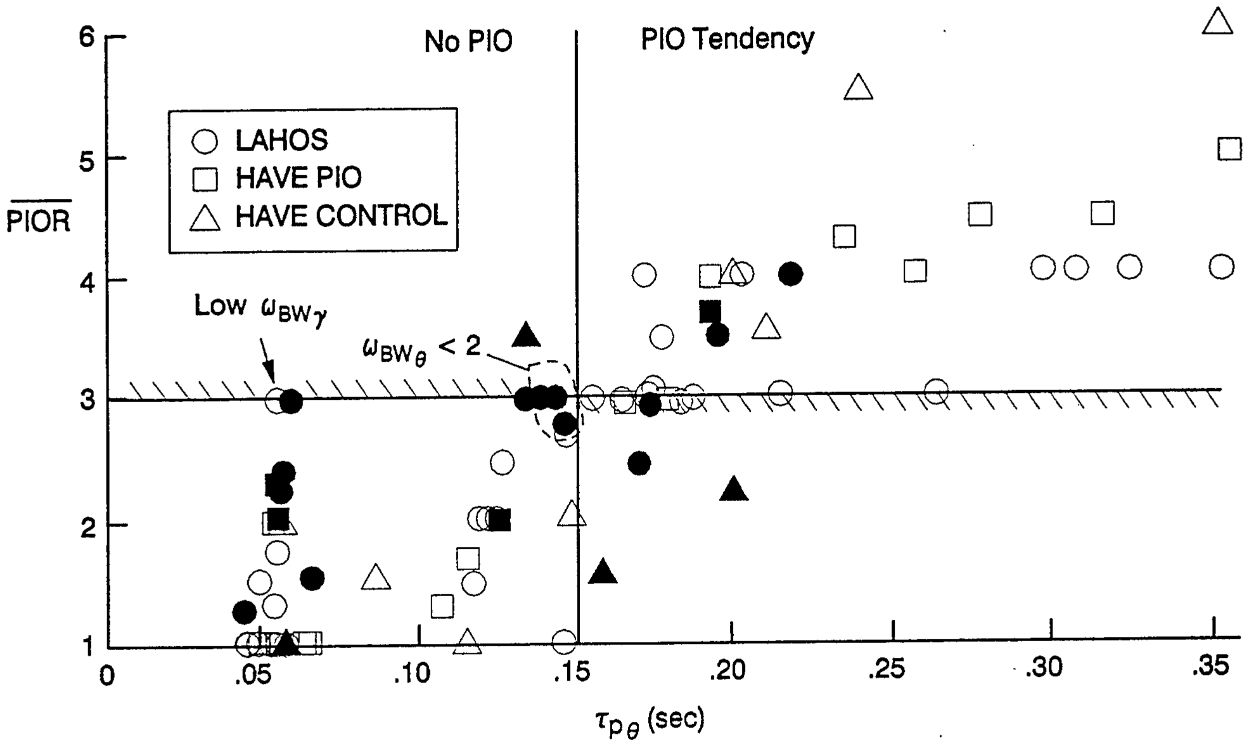


Figure E-58. Average PIO Ratings *vs*. Pitch Attitude Phase Delay for NT-33A Category C Data (Precision Offset Landing) (Solid Symbols Denote Excessive Dropback)

c. Data for Transport Aircraft: Precision Landing (Category C) Pitch Control

The Bandwidth characteristics of the configurations evaluated in the two TIFS programs (Refs. E-6 and E-7) were analyzed in detail earlier in this appendix. Figure E-59a summarizes the effectiveness of the criteria at predicting handling qualities Levels.

Predicted Level \ Actual Level	1	2	3
3	1	3	9
2	1	14	0
1	18	4	1

Predicted Correctly: 41/51 = 80%
Predicted Better: 5/51 = 10%
Predicted Worse: 5/51 = 10%

a) Handling Qualities Level

Predicted \ Actual	No PIO	PIO
PIO	6	14
No PIO	29	2

Predicted Correctly: 43/51 = 84%
Correctly Predict PIO: 14/20 = 70%

b) PIO Tendency

Figure E-59. Summary of Effectiveness of Bandwidth/Dropback Criteria for TIFS (Ref. E-6 and E-7) Data Base

Average PIO ratings are shown in Figure E-60 on the pitch attitude Bandwidth boundaries. All 51 configurations are plotted in Figure E-60; cases with excessive dropback are denoted with flagged symbols and cases with flightpath Bandwidth outside the Level 1 limits are denoted by solid symbols. Tentative PIO tendency boundaries, similar to (but not the same as) those for the NT-33A data, have been sketched based on the PIORs. These limits are as follows:

- If pitch attitude and flightpath Bandwidths are both Level 1, there is no PIO tendency, regardless of the value of phase delay. High dropback will usually result in PIO ratings greater than 1, but averages of less than 3.

- If pitch attitude Bandwidth is in the Level 1 region, PIOs are possible if flightpath Bandwidth ω_{BW_γ} is not Level 1. This suggests that the PIOs may be more a result of flightpath control than pitch attitude control; there is, unfortunately, no information to confirm this.

- If pitch attitude Bandwidth is not Level 1 and $\tau_{p\theta} \geq 0.15$ sec, the aircraft will always be susceptible to PIO.

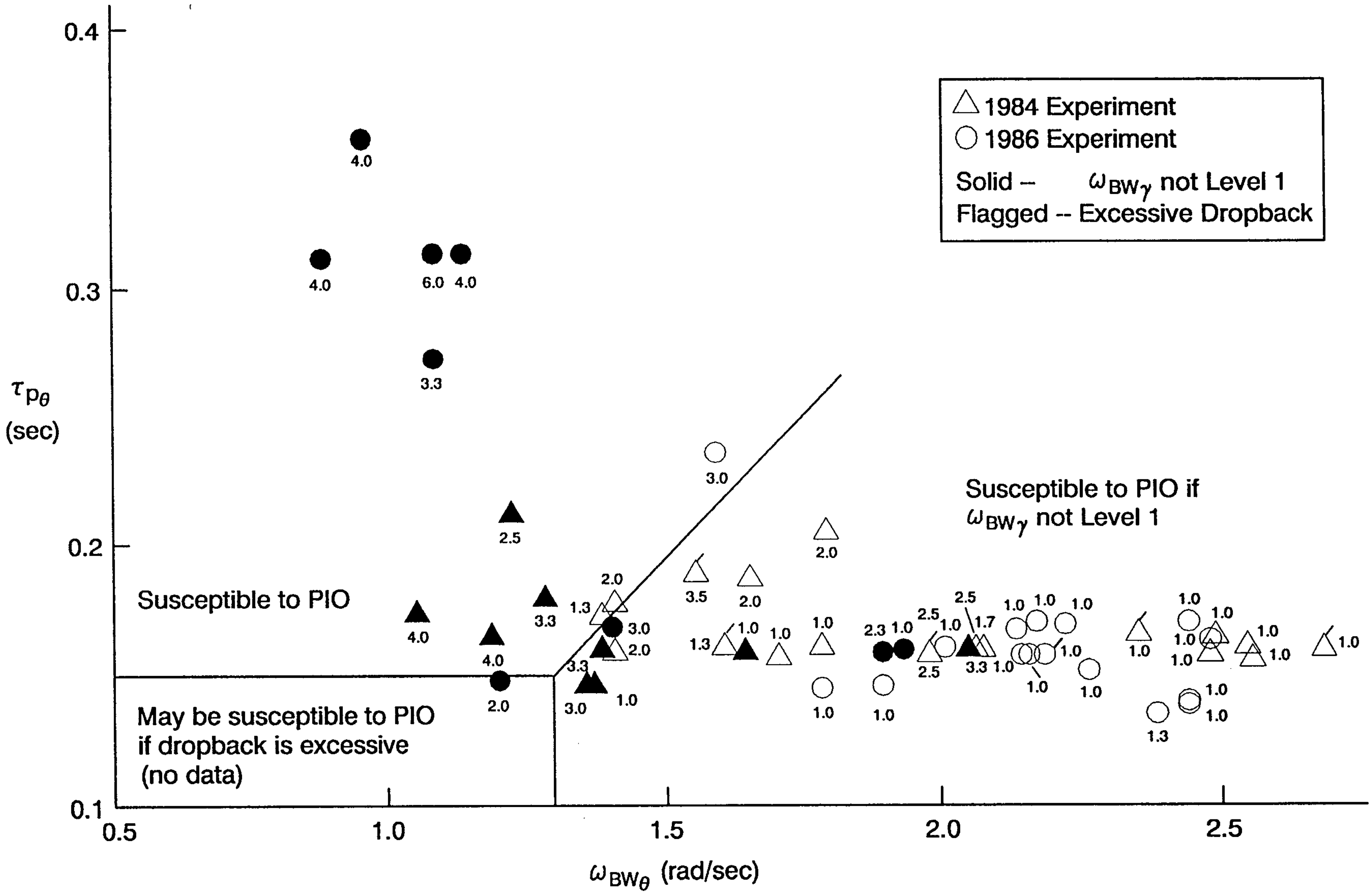


Figure E-60. Average PIO Ratings for TIFS configurations Compared to Pitch Attitude Bandwidth PIO Criteria

- Based on the NT-33A data, it is speculated that aircraft with low pitch attitude Bandwidth and low phase delay may be susceptible to PIOs if dropback is excessive. There are no cases solidly in this region in Figure E-60 to confirm this.

These tentative definitions work reasonably well to predict PIO tendencies based on the PIO ratings, as reflected in Figure E-59b. Forty-three of the 51 cases are correctly predicted, for a success rate of 84%. Of the 20 predicted PIO cases, 14 received PIORs of 3 or worse. This is not great agreement but it suggests some conservatism.

As with the LAHOS configurations, the overall phase delay determines PIO susceptibility, as Figure E-60 indicates. In fact, there is a very strong correlation between PIOR and $\tau_{p\theta}$.

4. *Prediction of PIO Frequency*

For the Smith-Geddes criteria, if a PIO is predicted the expected PIO frequency is the criterion frequency, ω_c, defined in Figure E-29. This hypothesis can be tested with the HAVE PIO configurations. For this we will use the nine obvious PIO cases. In addition, we will include the three pitch-bobble cases. The latter cases were considered to be PIOs by the author of Ref. E-37, and since PIO frequencies are quoted in the reference, we can determine if the Smith-Geddes criteria accurately predict frequency of the nose bobble as well. It is important to remember, however, that the Smith-Geddes criteria did not predict PIOs at all for these three configurations, so, whether the frequency is correct or not, there was no expectation for anything resembling a PIO for the cases.

In Figure E-61 the predicted PIO frequencies from the Smith-Geddes criteria are plotted against the measured frequencies from HAVE PIO. In three cases the PIO frequency plotted in Figure E-61 is different from that reported in Ref. E-37. For Configuration 2-B, Ref. E-37 lists the PIO frequency as 4.8 rad/sec (identical to the Smith-Geddes prediction, except the Smith-Geddes criteria do not predict a PIO for this case). The single time history of a landing published in the reference does not show any evidence of an oscillation at that frequency, however; instead, an oscillation is apparent at around 10.1 rad/sec, so this is the value plotted in Figure E-61. Similarly, for Configuration 3-6, the PIO frequency is published as 8.4 rad/sec but measured to be 7.5 rad/sec. And there is no frequency listed in Ref. E-37 for Configuration 3-8; a frequency of 7.2 was measured from the time history for the flare portion of the maneuver, and 6.0 rad/sec during the approach. These three cases are labeled in Figure E-61.

As Figure E-61 shows, the Smith-Geddes prediction is quite good as long as the PIO is a short-period oscillation and not pitch bobble. Since there is no standardized method for judging accuracy of the estimates, an assumption has been made that an estimate is accurate when it is within 0.5 rad/sec of

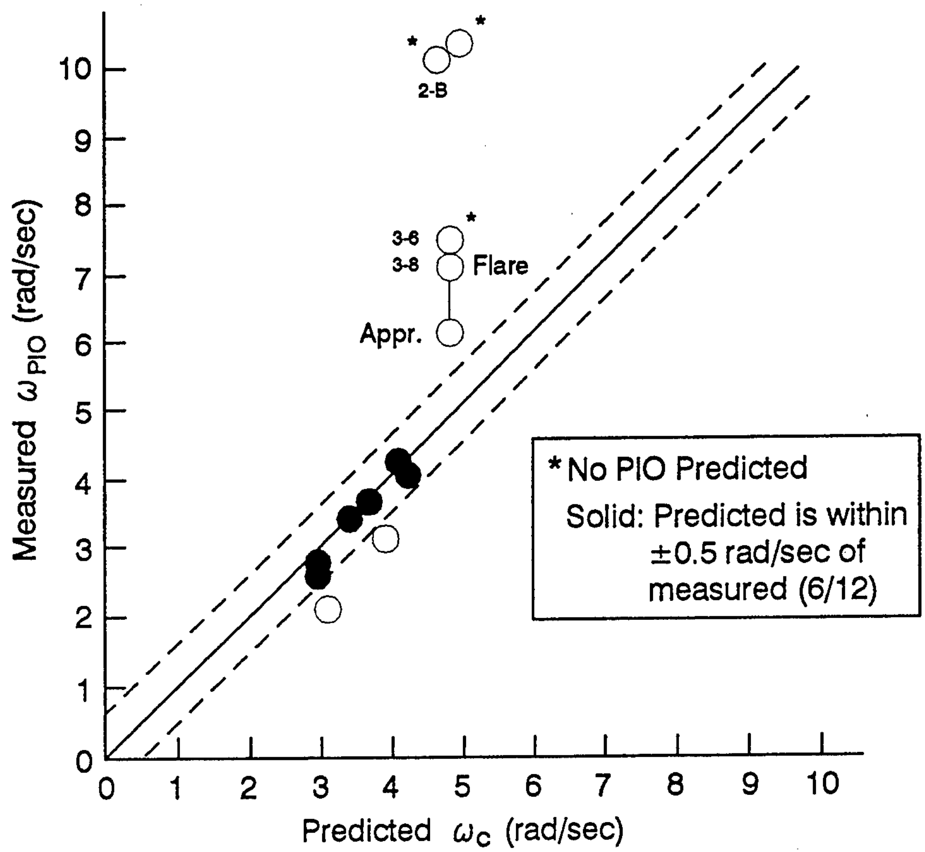


Figure E-61. Comparison of Predicted and Measured PIO Frequencies from HAVE PIO (Smith-Geddes Definition)

the measured value. On this basis, the Smith-Geddes criteria predict PIO frequency correctly half the time (6 out of 12), with three more cases that are very close, and four that are not close at all. Not surprisingly, the Smith-Geddes criteria will always predict PIO frequencies of somewhere between about 3 and 6 rad/sec, simply because of the definition of ω_c (Figure E-61).

In reviewing the PIOs in the HAVE PIO program, it was noticed that the PIO frequencies — including the oscillation frequencies for the pitch bobble cases — were very near the neutral-stability frequency, ω_{180}, of the pitch-attitude-to-stick-force transfer function. If a small factor of about 0.5 rad/sec is included, the correlation is even better. As evidence, Figure E-62 is a plot of predicted $\omega_{PIO} = \omega_{180}(\theta) + 0.5$ vs. measured PIO frequency. The correlation is excellent for all 12 cases, including all three bobble cases. The only estimate not within 0.5 rad/sec of the measured frequency is the flare portion for configuration 3-8.

This is very promising as a PIO frequency predictor for landing, and it seems reasonable to expect that a PIO, if it occurs, is going to be near the neutral-stability frequency of the aircraft alone, with no pilot in the loop.

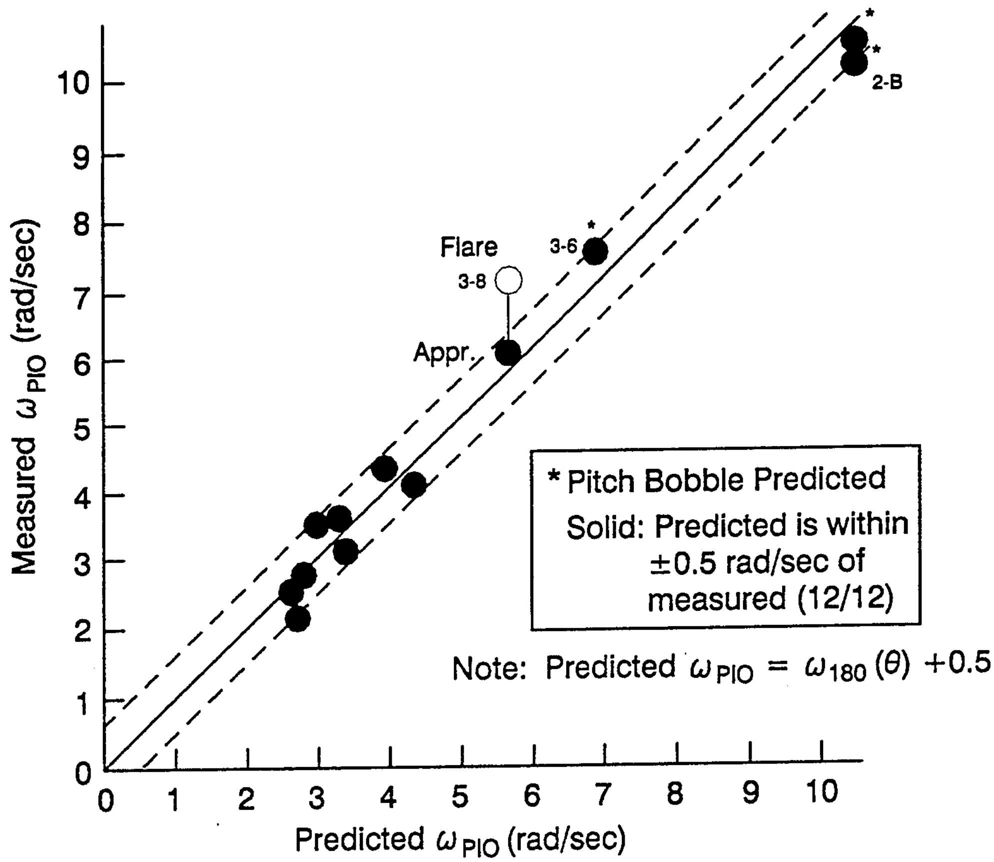


Figure E-62. Comparison of Predicted and Measured PIO Frequencies from HAVE PIO (ω_{180} Definition)

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